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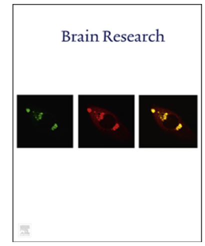

Research Report

The speed of learning instructed stimulus-response association rules in human: Experimental data and model

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ABSTRACT

Humans can learn associations between visual stimuli and motor responses from just a single instruction. This is known to be a fast process, but how fast is it? To answer this question, we asked participants to learn a briefly presented (200 ms) stimulus-response rule, which they then had to rapidly apply after a variable delay of between 50 and 1300 ms. Participants showed a longer response time with increased variability for short delays. The error rate was low and did not vary with the delay, showing that participants were able to encode the rule correctly in less than 250 ms. This time is close to the fastest synaptic learning speed deemed possible by diffusive influx of AMPA receptors. Learning continued at a slower pace in the delay period and was fully completed in average 900 ms after rule presentation onset, when response latencies dropped to levels consistent with basic reaction times. A neural model was proposed that explains the reduction of response times and of their variability with the delay by (i) a random synaptic learning process that generates weights of average values increasing with the learning time, followed by (ii) random crossing of the firing threshold by a leaky integrate-and-fire neuron model, and (iii) assuming that the behavioural response is initiated when all neurons in a pool of m neurons have fired their first spike after input onset. Values of $m=2$ or 3 were consistent with the experimental data. The proposed model is the simplest solution consistent with neurophysiological knowledge. Additional experiments are suggested to test the hypothesis underlying the model and also to explore forgetting effects for which there were indications for the longer delay conditions.

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1. Introduction

A unique human skill is the ability to understand task instructions. For instance: "Each time there is an animal in the pictures I will show you, press the red button". Over the years, numerous psychophysical experiments have made use of this ability. However, only recently has research started to focus on how the brain converts instructions into mental

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programs. This is the area of "instruction-based learning (IBL)" (Bugmann, 2009, Ruge and Wolfensteller, 2010; Bugmann, 2012, Hartstra et al., 2012, Wolfensteller and Ruge, 2012) or "rapid instructed task learning (RITL)" (Cole et al., 2010).

The observations that IBL (i) takes at most a few seconds (see e.g. Ruge and Wolfensteller, 2010), (ii) is a one-shot process and (iii) is assumed to establish relations between distant brain areas, have triggered the development of a computational model of fast learning across several neuronal relays (Bugmann, 2009, 2012). However, there were no hard data on the actual speed of human learning and no clear information on how fast synapses can learn that could be used to constrain a model.

The questions addressed in this paper are: How fast is "fast" learning? Is the behavioural learning time consistent with the hypothesis that stimulus-response (SR) rules are encoded in synaptic weights?

To answer the first question (Section 2), we set up an experiment to determine the actual behavioural learning time of humans. In this experiment, participants were visually presented for a very short time (200 ms) with a stimulus-response rule to learn. After a time interval of between 50 and 1300 ms they were then asked to apply the rule. The expectation was that they would not be able to reply before learning was completed, causing increased response times for short intervals.

Answering the second question was more convoluted. First, we established what anatomical pathways were most likely to support fast learning (Section 3). Secondly, we used pathway assumptions to analyse the experimental response times in terms of a constant propagation time added to a delay-dependent rule retrieval process, allowing us to characterise the learning element of the circuit (Section 4). We then sought to explain the characteristics of the learning element in terms of synaptic learning rule and firing of a leaky integrate-and-fire (LIF) model of a neuron, or a number of those (Section 5). Once we were satisfied that a LIF model-based neural system could explain the data, we used that model to infer the values of the synaptic weights reached after different delays in the experiment. This revealed the time course of synaptic learning during SR rule presentation and in the delay before rule retrieval.

The results of this work show that experimental data are consistent with an involvement of the hippocampus in both simple reaction time tasks and SR encoding and retrieval tasks. These require synaptic modifications as fast as seems physically possible. The variability of the response times is consistent with a few independent neurons being required to encode the SR rule.

2. Experimental procedures

2.1. Method

2.1.1. Participants

Eleven people, eight male and three female, participated in this experiment with ages ranging from 21 to 62 years (mean=42.9 years, SD=13.96 years).

2.1.2. Procedure

Participants were required to learn a simple stimulus-response (SR) rule and then rapidly apply that rule to a single following stimulus. The rule instruction took the form of an image showing a capital letter in the middle of the image along with either a left-pointing or right-pointing arrow, also placed to the left or the right of the letter (Fig. 1B). The letter indicated the stimulus and the arrow the required response, a key press performed using right or left index finger (left or right shift key on keyboard). This rule was displayed for 200 ms, followed by a blank screen with a duration (termed the "delay" D) randomly selected from 50, 100, 300, 500, 700, 900, 1100, or 1300 ms. After the blank screen, the test stimulus was presented until the response was produced or until a 5 s timeout (Fig. 1A). If the test stimulus was the same letter as that used in the previously displayed SR rule then participants had to react using either left or right index fingers according to the arrow indicated by the rule. If the stimulus did not correspond to letter of the prior rule then participants were asked to press the space bar with either thumb. Each session consisted of a list of 160 SR rules randomly created from combinations of each of 26 capital letters and left and right response directions. Of these, there were 96 trials where the stimulus matched that used in the rule, and 64 where there was a mismatch. Each session was preceded by 20 baseline reaction time measurements, where participants immediately responded to left or right arrows by pressing keys with left or right index fingers as quickly as possible. After this, five familiarisation trials of the main procedure were run. Participants completed such a session four times, each time with a different random ordering of the 160 trials. Each session took approximately 8 min to complete, with participants typically leaving a few hours between each session.

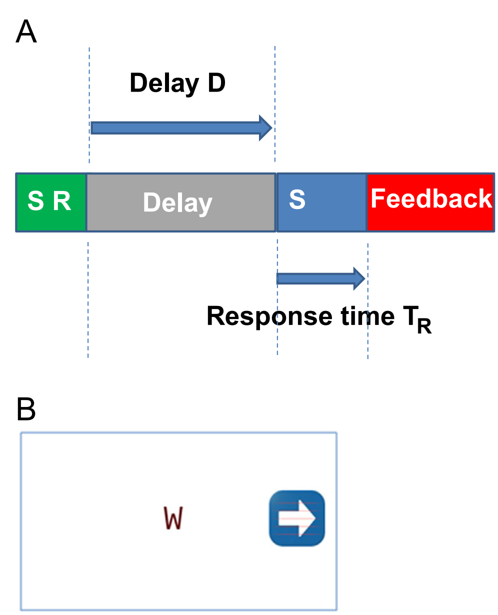

Fig. 1 – (A) Time line of the experiment. The stimulus-response rule is presented for 200 ms. The delay *D* varies between 50 ms and 1300 ms. (B) Format of the stimulus-response (S-R) rule presentation. In this example, the arrow instructs to press the right shift key (response R) when the stimulus *W* is presented alone.