



Brief communication

Serial reaction time performance following right parietal lobe damage

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The serial reaction time task (SRT) is used to assess implicit sequence learning. Neuroimaging studies implicate parietal involvement; however, the necessity of this area is unclear. We tested six unilateral right parietal patients and compared their performance to matched controls. Both groups showed similar levels of learning and explicit awareness. Two patients with the largest lesions extending into either frontal or cerebellar regions showed no learning. These data suggest that implicit sequence learning can occur despite damage to the right parietal lobe.

In the serial response time (SRT) task, participants make speeded key press responses to visual cues. Unbeknownst to participants, a specific sequence is embedded and repeated. Reaction times typically become faster with repetition, only to slow down when a novel stimulus order is introduced. Because many participants fail to notice the sequence, performance on the SRT is often considered a measure of implicit learning (Nissen & Bullemer, 1987).

The SRT task is frequently used to investigate how the brain implicitly learns sequences. Neuroimaging studies using the SRT paradigm consistently report either bilateral parietal activations (Keele, Ivry, Mayr, Hazeltine, & Heuer, 2003; Poldrack *et al.*, 2005; van der Graaf, Maguire, Leenders, & de Jong, 2006) or right parietal activations (Bischoff-Grethe, Martin, Mao, & Berns, 2001; Olson *et al.*, 2006). However, prior neuropsychological studies of performance on the SRT task have not examined the effects of damage to this region. Whether or not it plays an essential role in sequence learning is unknown. To evaluate this, we administered the SRT task to a group of patients with right parietal lobe damage.

Methods

Participants

The patient population consisted of six patients with unilateral right parietal lobe damage, aged 40–75 years (mean 58.6 ± 13.9, one male), with an average of 12.7 years

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of education. All patients were right-handed, high functioning, free from neglect, and visual field cuts. Neglect was assessed using several tasks: Albert's line cancellation; clock face drawing; greyscales; and stimulus extinction. Patient lesions can be viewed in Figure 1 and patient descriptions can be found in Table 1.

Patients' performance was compared to that of nine age-matched ($M = 55.7$ years, range 43–71 years, four males) and education-matched ($M = 14.8$) controls. Controls were right-handed and free of neurological disorders. All participants were paid \$15 per hour for their participation. Written consent was given according to an Institutional Review Board approval from the University of Pennsylvania.

Task

The stimuli consisted of four horizontally arrayed squares on a medium grey background. Each square became active when filled with its own distinct colour (green, blue, red, and yellow from left to right). Participants were instructed to respond by pressing the spatially corresponding key as quickly and as accurately as possible. A new

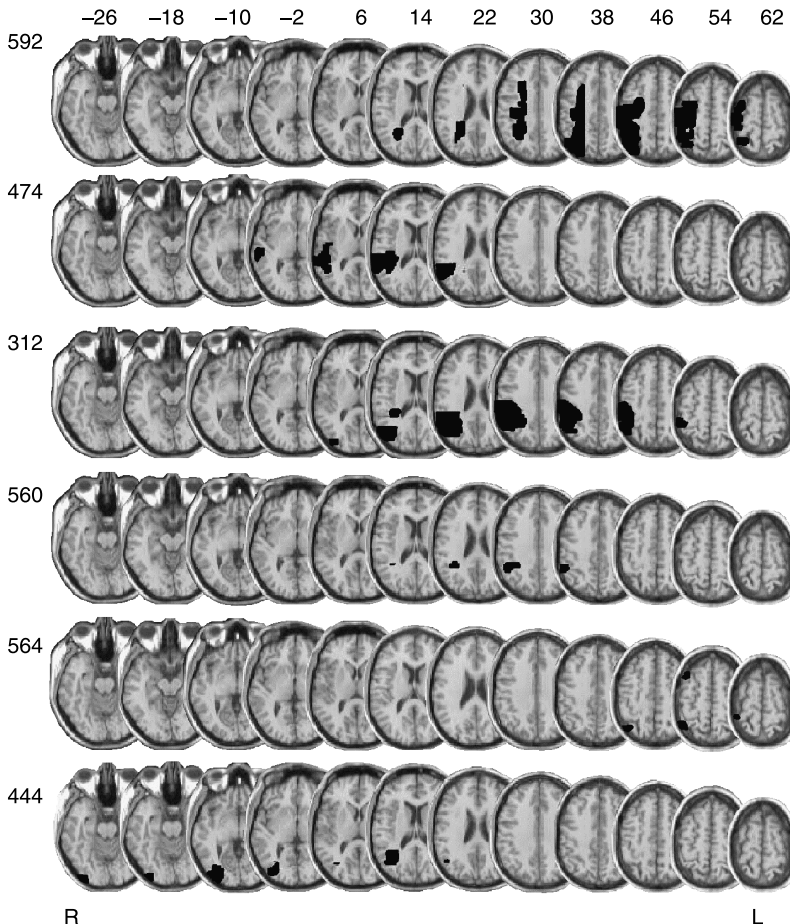


Figure 1. Patient lesions. The lesions were traced on a standard brain by a consulting neurologist using MRIcro software. Brains are depicted with the right hemisphere on the left.

Table 1. Patient characteristics. Edu, education in years; MCA, middle cerebral artery; L, left; Moya Moya, a rare cerebro-vascular disorder; AVM, arteriovenous malformation; I, inferior; S, superior

Participant	Age	Sex	Edu	Injury date	Aetiology	Lesion location	Frontal involvement
592	40	F	13	2001	MCA infarct, Moya Moya	S frontoparietal	+
474	47	F	12	1995	MCA infarct	I parietal, L caudate	-
312	57	F	17	1981	AVM resection	S parietal, cerebellar atrophy	-
560	60	M	12	2003	MCA infarct	I parietal	-
564	73	F	10	2001	Infarct	S parietal, frontal	+
444	75	F	12	2002	MCA infarct	I temporoparietal	-
Mean	58.6	5 F/1 M	12.7				

square activated immediately following a key press. Participants used the index and middle fingers of each hand on the *D*, *F*, *J*, and *K* keys of a computer keyboard. One patient (592) used the four fingers of her right hand on the *F*, *G*, *H*, and *J* keys due to hemiparesis of the left hand.

The invariant sequence was eight-item long consisting of two key presses from each finger. This sequence length was chosen in order to be slightly easier for the patients than commonly used longer sequences and to show learning more quickly. The eight-item invariant sequence repeated 80 times and was followed by a test phase, which controlled for earlier reaction time improvements attributable to general features of the task by presenting a pseudo-random order of stimuli. The test phase consisted of 120 pseudo-randomly ordered button presses. The final time bin was pseudo-random to ensure that no three-step subsequence from the repeated sequence reoccurred. The experiment was performed without pause and lasted approximately 15 minutes.

After completing the task, we tested explicit awareness by asking the participants whether they noticed the embedded sequence. Participants were then asked to type the remembered pattern into the computer.

Analysis

The dependent measure was key press reaction time (RT). Incorrect trials and outliers were excluded on a per-participant basis ($RT > \text{mean} + 2 \times \text{standard deviation}$). Trials were binned into five epochs: First to fourth consisted of the repeated-sequence trials (20 repetitions or 160 key presses) and the fifth consisted of the 120 pseudo-random stimuli. Mean RTs were calculated and analyzed using a repeated measures ANOVA with SPSS 11.0.

Results

Accuracy was high in both groups (controls, $M = 0.97 \pm 0.02$; patients, $M = 0.95 \pm 0.04$). Learning was compared using a two-factor repeated measures ANOVA on group (patient, control) and epoch (first to fifth); results are depicted in Figure 2. The patients were an average of 348 ms slower than the controls ($F_{1,13} = 8.50$, $p < .01$), a finding commonly observed in lesion populations. Of interest, both groups showed an RT

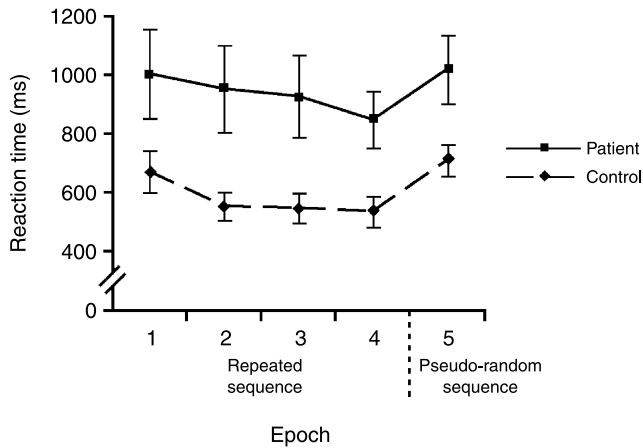


Figure 2. Reaction time by trial epoch. In epochs 1–4, participants pressed keys in response to a repeated eight-trial sequence of visual stimuli. During epoch 5, the stimuli appeared in pseudo-random order to test learning.

improvement over the training epochs ($F_{4,52} = 9.10$, $p < .001$) and there was no significant interaction between group and epoch ($F_{4,52} < 1$, $p = ns$).

To assess implicit learning in more detail, we examined the change in RT between the fourth and fifth epochs. This measure captures the change in performance when switching from a predictable to an unpredictable pattern. This t test was significant for control ($t_8 = 4.37$, $p = .002$) and patient ($t_5 = 2.94$, $p = .03$) groups.

Last, a comparison of the difference scores (epoch 5 – epoch 4) for each group found no difference in the magnitude of learning between patients and controls ($t_{13} = 0.04$, $p = .97$).

Looking at individual performance, only one patient, patient (#560), showed fairly flat performance over the four sequence epochs. However, he evidenced learning in two other ways: his performance slowed during the pseudo-random epoch and he noticed the presence of a pattern during the test of conscious memory (see below) that followed the training session.

It is possible that with a larger sample of patients, we would have observed relatively poorer SRT learning in the patient group. To estimate our chances of finding this, we conducted a power analysis suggesting that approximately 70 patients would be needed in order to detect a small effect size ($= .1$) with high power ($\beta = 0.8$). This finding indicates that there may be small differences in the SRT learning abilities of patients and controls, which become evident when a large population is tested, but that such differences are not observed at the individual or small-group level.

Test of conscious memory

Two out of the nine controls (22%) and two out of the six patients (33%) claimed to notice a repeating pattern during the task. One control, unable to reproduce the pattern by typing, verbally described the first five steps in terms of the colours that appeared. One patient successfully retyped the first five key presses of the pattern. No other participant produced more than three steps of the learned sequence. These findings suggest that (a) patients and controls did not differ in access to explicit awareness and (b) for most participants, learning was implicit.

Discussion

Sequence learning deficits on the SRT task have been observed in several patient populations. Not surprisingly, damage to motor regions such as the cerebellum and basal ganglia causes sequence learning deficits (Doyon *et al.*, 1998; Gomez-Belderrain, Garcia-Monco, Rubio, & Pascual-Leone, 1998; Molinari *et al.*, 1997; Willingham & Koroshetz, 1993). Further analyses have indicated that the cerebellum and basal ganglia may be critical for motor performance and/or the formation of higher order sequences, rather than for the formation of learning *per se* (Seidler *et al.*, 2002).

Prefrontal damage to the right, but not left hemisphere, causes impaired sequence learning (Gomez-Belderrain, Grafman, Ruiz de Velasco, Pascual-Leone, & Garcia-Monco, 2004; Keele *et al.*, 2003). Accordingly, TMS to prefrontal cortex disrupts sequence learning for spatial but not non-spatial sequences (Robertson, Tormos, Maeda, & Pascual-Leone, 2001). In contrast, bilateral medial temporal lobe damage does not dramatically affect sequence learning (Curran, 1997) and, as seen here, neither does right parietal lobe damage.

Although damage to the right parietal lobe does not affect sequence learning, it is possible that damage to the left parietal lobe will impair sequence learning. Left parietal lobe activity is associated with motor attention and intention (Rushworth, Krams, & Passingham, 2001). The underlying computations required for monitoring and planning actions may support those required for implicitly learning action sequences.

Acknowledgements

The authors thank Anjan Chatterjee and Marianna Stark for allowing us to use their patient database and David Drowos for assistance with testing controls.

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Received 11 September 2007; revised version received 3 November 2007