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Parietal damage impairs learning of a visuomotor tracking skill

Sara Cavaco [a,b,*,1], Steven W. Anderson [a], Kuan-Hua Chen [a], Armando Teixeira-Pinto [c], Hanna Damasio [d]

[a] Division of Behavioral Neurology and Cognitive Neuroscience, University of Iowa Carver College of Medicine, Iowa City, IA, USA
[b] Unidade de Neuropsicologia, Centro Hospitalar do Porto, Porto, Portugal
[c] Screening and Test Evaluation Program, Sydney School of Public Health, University of Sydney, Sydney, Australia
[d] Dornsife Cognitive Neuroscience Imaging Center and Brain and Creative Center, University of Southern California, Los Angeles, CA, USA

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ABSTRACT

This study evaluated the consequences of damage to the parietal lobe for learning a visuomotor tracking skill. Thirty subjects with a single unilateral brain lesion (13 with and 17 without parietal damage) and 23 demographically comparable healthy subjects performed the Rotary Pursuit task. For each group, time on target increased significantly across the four learning blocks. Subjects with parietal lesions had smaller improvements on the Rotary Pursuit from the 1st to the 4th block than subjects with lesions in other brain areas and healthy comparison subjects. The improvements on task performance from the 1st to the 2nd and from the 1st to the 3rd learning blocks were similar between groups. The parietal lobe appears to play an important role in the acquisition of a new visuomotor tracking skill, in particular during a relatively late phase of learning.

1. Introduction

The ability to learn and retain new motor skills is critical for many daily life activities (e.g., cooking, driving, tying shoelaces). The current knowledge on the neural basis for acquiring this type of non-declarative information is still limited. Evidence from different lines of research suggests that the neural structures involved in motor skill learning depend on task demands and learning stage (e.g., Gabrieli et al., 1997; Shadmehr and Holcomb, 1997; Floyer-Lea and Matthews, 2004; Cavaco et al., 2011). The contribution of the parietal cortex to motor skill learning is not fully understood.

Rotary Pursuit (RP) is one of the oldest (Ammons, 1947) and most widely used skill learning paradigms (e.g., Grafton et al., 1994; Tranel et al., 1994; Gabrieli et al., 1997; Schmidtke et al., 2002; Cavaco et al., 2011). It requires tracking a predictable moving stimulus (e.g., a circle or a triangle) with a stylus. Learning of the skill with practice is inferred by the increasing time of contact between the stylus and the target. The ability to learn and retain this visuomotor tracking skill is known not to depend on the integrity of the medial temporal region (e.g., Milner, 1962; Tranel et al., 1994). On the other hand, human lesion studies have established that the striatum (e.g., Gabrieli et al., 1997; Schmidtke et al., 2002; Cavaco et al., 2011) plays a critical role in learning the RP skill and there is evidence that damage to the cerebellum can also disrupt learning this skill (Hatakenaka et al., 2012). Frontal lobe damage has produced mixed results regarding learning visuomotor tracking skills (Ackermann et al., 1996; Beldarrain et al., 2002; Schmidtke et al., 2002). Ackermann et al. (1996) and Beldarrain et al. (2002) reports suggest that the role of the frontal lobes in the acquisition of a visuomotor tracking skill depends on task conditions (e.g., sequential pattern vs. random motion of the target; mirror reversed vs. unreversed tracking). These two studies did not use the RP paradigm. Schmidtke et al. (2002) study explored the RP performance of 20 subjects with frontal lobe lesions and did not observe a significant learning impairment.

Involvement of the frontal lobes in RP skill learning has been suggested by functional neuroimaging results (Grafton et al., 1994; Hatakenaka et al., 2007, 2012). Grafton et al. (1994) reported that healthy right-handed subjects had increased activation of right parietal cortices (the inferior parietal cortex – Brodmann area 40 and the precuneus – Brodmann area 7), among other activation changes (i.e., increased primary motor cortex, supplementary motor area – SMA, insula, and anterior cerebellar activation; and decreased activation of the hippocampus, the right posterior insula, and the basis pontis) during the initial practice of the RP task.

* Corresponding author at: Division of Behavioral Neurology and Cognitive Neuroscience, University of Iowa Carver College of Medicine, Iowa City, IA, USA.
E-mail address: sara-cavaco@uiowa.edu (S. Cavaco).
[1] Postal address: Department of Neurology, 2155 RCP, University of Iowa Hospitals and Clinics, Iowa City, IA 52242, USA.

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After extensive practice of the RP (i.e., when a relative plateau in the performance had been reached), the authors observed an increased bilateral activation of parietal cortices (i.e., right Brodmann area 40/7 and left Brodmann area 40), among other activation changes, namely increased left putamen, and left inferior premotor cortex; and decreased activation of the right putamen and the left frontal cortex. These positron emission tomography (PET) findings suggest a bilateral parietal involvement during RP skill learning.

Similar to Grafton's report, Hatakenaka et al. (2007, 2012) observed task-related (i.e., activation changes during task performance in comparison to rest state) increased activation in the right parietal regions and other cortical regions (i.e., prefrontal cortex, pre-supplementary motor area – preSMA, SMA, dorsal premotor cortex, left sensorimotor cortex – SMC). However, these later functional near-infrared spectroscopy (NIRS) studies did not observe learning-related activation changes in the parietal cortex (i.e., no activation change in the parietal lobe, including SMC, with task repetition). The authors reported instead a gradual shift in the activation center from the preSMA to the SMA with repeated practice of the RP task. The inconsistent functional neuroimaging findings regarding learning-related parietal cortex activation changes could be explained by differences in the practice protocol and the neuroimaging methods used by the two studies. Grafton's subjects performed more trials throughout a longer period of time, which allowed them to consolidate and automatize the skill. In addition, different neuroimaging methods were used in those studies (PET vs. NIRS).

There is growing evidence from human lesion studies that the parietal cortices are critical to learn other non-declarative information, such as implicit motor sequences (Beldarrain et al., 2008) and motor adaptation (Mutha et al., 2011), and to perform well learned skilled movements (Haaland et al., 2000). Cortical areas along the visual dorsal stream (from the occipital to the posterior parietal region) have been implicated in egocentric coding of spatial information (viewer-centered) and in visual control of action (Goodale and Milner, 1992; Snyder et al., 1997; Galati et al., 2000; Committeri et al., 2007). Functional neuroimaging of healthy individuals has provided evidence that the inferior parietal cortex is particularly involved in monitoring regular predictable target trajectories (Vallesi and Crescentini, 2011). It has been demonstrated that damage to the posterior parietal cortex can disrupt error correction when there are quick changes in the position of a target (Desmurget et al., 1999) and it has been well established that parietal lesions may affect the anticipatory eye movement response required to follow a predictably moving target (Braun et al., 1996; Heide et al., 1996; Burke et al., 2013). However, it is still unknown whether damage to the parietal cortex disrupts learning of visuomotor tracking skills. To address this issue, we studied the RP performance of individuals with unilateral brain damage involving the parietal lobe and contrasted their behavior to that of subjects without damage in this brain region.

2. Material and methods

2.1. Subjects

Thirty subjects with unilateral damage (Tables 1 and 2) were selected from the Iowa Neurological Patient Registry in the Division of Behavioral Neurology and Cognitive Neuroscience at the University of Iowa (15 women and 15 men; mean age = 62.8, sd = 6.4; mean education = 14.7, sd = 2.9). Subjects with damage in the basal ganglia or the cerebellum were not included, because these brain regions have been implicated in learning of the RP skill (e.g., Gabrieli et al., 1997; Schmidtke et al., 2002; Cavaco et al., 2011; Hatakenaka et al., 2012). Lesions smaller than 5000 mm^3 or larger than 65,000 mm^3 were not included. Evidence of progressive dementia or history of psychiatric disorder was considered an exclusion criterion. All brain lesion subjects were studied behaviorally and neuroanatomically at least 14 months after their neurologic event (mean = 87 months, sd = 61), at which time their neurologic status and neuropsychological profiles were stable. None of the participants had neglect at the time of the assessment.

Twenty-three individuals without history or evidence of neurological or psychiatric disorder (HC group; 12 women and 11 men; 18 right-handed and 5 left-handed; mean age = 62.5, sd = 7.9; mean education = 14.9, sd = 2.5) were recruited in the community (Table 2).

In accordance with the policies of the University of Iowa Institutional Review Board, all participants provided informed consent.

2.2. Procedures

2.2.1. Neuroimaging examination

Visual inspection, description, and size calculation of the participants' lesions were based on axial computerized tomography or high-resolution magnetic resonance scans. Axial computerized tomography scans were obtained for one subject (subject #24) in a Toshiba Aquilion scanner. For all the other subjects, thin-cut magnetic resonance images were obtained in GE Signa Infinity scanner operating at 1.5 T or in Siemens Magnetom Tim Trio scanner operating at 3.0 T. For lesion size calculation, the lesions were manually traced on the scans using Brainvox (Frank et al., 1997).

2.2.2. Neurological examination

Brain damage subjects' upper limb motor and sensation data were collected from the most updated medical records. The attending neurologist conducted the neurological examination of the brain lesion subjects during their regular clinical appointments.

2.2.3. Neuropsychological evaluation

Brain damage subjects underwent a comprehensive neuropsychological evaluation, which included the Wechsler Adult Intelligence Scale III or IV (WAIS) – Digit Span (DS) and Block Design (BD) subtests; Iowa-Chapman Reading Test (ICRT); Auditory Verbal Learning Test (AVLT) – Immediate Recall (IR) and Delayed Recall (DR); Judgment of Line Orientation (JLO); Complex Figure Test (CFT) – Copy and DR; Controlled Oral Word Association (COWA); and Trail Making Test (TMT) – A and B.

2.2.4. Skill learning task

Participants were instructed to maintain contact between a stylus held in their preferred hand and a small illuminated square, and to follow the square while it moved clockwise at a constant speed on the rotating turntable (26.5 cm in diameter, for the inner circle; 2 cm wide for the track). The contact between the stylus and the target square produced a small click sound. The speed of the roundtable was adjusted to the individual participant level of performance during four pre-testing practice trials. The speed (i.e., 15, 30, 45 or 60 rotations per minute – RPM) associated with a practice performance of ~25% on target was chosen for the test trials. RP testing consisted of two sessions separated by approximately 20 min of other psychometric testing, with two blocks of four trials each per session. Between the first and the second and between the third and the fourth blocks, there were one-minute breaks. The dependent measure was total time on target, recorded for each 20 s trial.

2.2.5. Statistical analyses

For group comparisons of demographic characteristics and of neuroimaging, neurological and neuropsychological evaluations, we used Chi-square tests or Fisher's exact for categorical variables and *t*-test or one-way ANOVA for continuous one.

For the 4 blocks of the skill learning evaluation we used a general linear model with repeated-measures and applied appropriate contrasts to build the hypothesis tests of interest. No correction for multiple comparisons was applied given that the hypotheses tested were pre-specified. The adjustment for lesion side and size was done by adding these covariates to the GLM model.

Pearson's correlations were applied to explore possible associations between RP measures and demographic, neuroimaging, and neuropsychological variables.

A significance level of $p < 0.05$ was set for all hypothesis tests. The statistical analysis was performed using IBM SPSS v.21.

3. Results

3.1. Neuroimaging examination

Based on the site of damage, subjects were divided in two groups (Tables 1 and 2): 13 with parietal damage (PL group) and 17 with damage to other brain areas but not to the parietal lobe (OBA group). Fig. 1 shows an example of a PL subject. Five PL subjects