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Research report

Relation between reaction time and reach errors during visuomotor adaptation

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ABSTRACT

Adaptation of reaching movements to visuomotor transformations is generally thought to involve implicit or procedural learning. However, there is evidence that explicit or cognitive processes can also play a role (Redding and Wallace, 2006 [31]). For example, the early phase of adaptation to a visuomotor rotation appears to involve spatial working memory processes linked to mental rotation (Anguera et al., 2010 [11]). Since it is known that cognitive processes like mental rotation lead to larger reaction times (Georgopoulos and Massey, 1987 [12]), here we explored the relation between reaction time (RT) and reach error reduction. Two groups of subjects adapted their reaching movements to a 60° visuomotor rotation either without RT constraints or with RT limited to 350 ms. In the unconstrained group, we found that adaption rate varied widely across subjects and was strongly correlated with RT. Subjects who decreased hand direction error (DE) rapidly exhibited prolonged RTs whereas little RT cost was seen in subjects who decreased DE gradually. RTs were also correlated with after-effects seen when the visuomotor rotation was removed. Subjects with the longest RTs exhibited the smallest after-effects. In the RT constrained group, all subjects exhibited gradual DE adaptation and large after-effects, similar to the fast responders in the free group. These results suggest that adaptation to a visuomotor rotation can involve processes that produce faster error reductions without increasing after-effects, but at an expense of larger reaction times. Possible candidates are processes related to spatial working memory, and more specifically, to mental rotation.

1. Introduction

An important aspect of motor learning involves mastering novel transformations between motor commands and sensory outcomes. Such learning has been investigated by examining how people adapt their reaching and throwing movements to altered visual feedback produced by displacing or inverting prisms (e.g., [1–3]) or using visuomotor rotations where the viewed position of the hand (or cursor representing the hand) is rotated about a start position (e.g., [4–7]).

Previous work has shown that adaptation of arm movements to visuomotor perturbations can be affected by secondary tasks [8]. However, the deleterious effects of such tasks is most significant during the early stages of motor adaptation, leading to the suggestion that cognitive resources could be needed mostly at the beginning of the training [9]. It has been suggested that working memory processes might contribute to visuomotor learning [10] and this suggestion is supported by recent evidence showing that performance on a spatial working memory test correlated with the rate of early visuomotor learning [11].

One way to test if a spatial working memory component related to mental rotation participates in visuomotor learning would be to measure reaction times. Georgopoulos and colleagues [12,13] found that when subjects are required to generate straight line reaches to a location that is rotated away from the visual target, reaction time (RT) increased with rotation angle. They also found that across subjects, RT on the reaching task was positively correlated with RT on a mental rotation task, suggesting a role of a mental rotation process in the reaching task. The aim of the current study was to test if there is any correlation between RT and reach error reduction in a visuomotor adaptation task that could suggest the participation of cognitive processes linked to spatial working memory or mental rotation.

We examined adaptation of reaching movements to a visuomotor rotation of 60°. We hypothesized that if a cognitive strategy was implemented to more rapidly reduce reach direction errors, then adaptation rate would be directly proportional to RT. Because cognitive strategies to reduce errors do not necessarily result in after-effects [1,14–16], we also predicted that subjects who exhib-

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ited the largest RTs at the end of adaptation would exhibit the smallest after-effects following removal of the visuomotor rotation. Finally, we also predicted that if we restricted RT, any working memory or mental rotation process would be compromised, resulting in gradual visuomotor adaptation with large after-effects.

2. Methods

2.1. Subjects

Twenty-seven subjects were recruited from the Queen's University undergraduate and graduate student community after the experimental protocol received approval by the Queen's University General Research Ethics Board. These subjects provided informed consent and received course credits or monetary compensation for their participation.

2.2. Apparatus

Subjects grasped the handle of a lightweight manipulandum (Phantom Haptic Interface 3.0, Sensable Devices, MA) mounted on an air sled that slid across a horizontal glass surface. The manipulandum measured the position of the handle at 1000 Hz with a spatial resolution of 0.1 cm. A virtual reality display system was used to present the start position, the target, and the position of the hand; all represented as circles 2 cm in diameter, in the horizontal plane of the hand. This system consisted of a CRT projector (Electrohome 9500 Ultra with a refresh rate of 150 Hz) that projected onto a screen positioned above a semi-silvered mirror located midway between the screen and the plane of hand motion. Subjects could not see their actual hand or arm.

2.3. Tasks and groups

Three groups of 9 subjects were tested. Two groups adapted to a visuomotor rotation of 60°. Subjects in the unconstrained RT group were told to reach to the target as soon as it was presented but we did not set any time limit for their RT. In the constrained RT group we set a time limit of 350 ms to start the reaching movement following target presentation. If RT exceeded this time limit, the visual display was blanked and a new trial was started. This time limit was chosen for two reasons. First, pilot work showed that subjects could consistently initiate their movements within 350 ms and that doing so resulted in gradual adaptation. Second, the results from the unconstrained group showed that at the end of the practice phase, and at the end of the de-adaptation phase, most subjects exhibited RTs slightly less than 350 ms. A third group performed in a 60° mental rotation task. This mental rotation group was included to estimate the mental rotation RT under our experimental conditions.

2.4. Procedure

Subjects began each trial by aligning the hand cursor to a central start position, located about 10 cm below the shoulder in the mid-sagittal plane. Targets were presented in one of the 8 locations directed radially from the start position. The targets were evenly spaced 45° apart and located 15 cm from the start position. Targets were presented in blocks containing all 8 targets and target order was randomized within each block.

In the visuomotor rotation experiments, subjects began with 3 blocks (24 trials) of normal reaching and then completed 40 blocks (320 trials) with the visuomotor transformation (a 60° counterclockwise rotation of the hand cursor) imposed. They then completed 20 blocks of normal reaching, allowing us to assess after-effects. Subjects were asked to move the cursor controlled by the hand as soon as the target appeared. They were asked to make a continuous out and back movement and not to make on-line movement corrections during the trial. Subjects could see the hand cursor during the movement along with the start position and target.

Subjects in the mental rotation group began with 3 blocks (24 trials) of normal reaching and then completed 20 blocks (160 trials) of the mental rotation task in which they were asked to move the cursor to a location rotated 60° clockwise from the target about the start position. Similar to the unconstrained visuomotor rotation group, they were asked to move as soon as the target appeared and to make a continuous out and back movement equal in amplitude to the distance to the target (i.e., 15 cm). The start position and target were displayed throughout the trial. During the movement, the hand cursor was removed from view. After the movement, a circle (2 cm in diameter) was displayed at the rotated goal (i.e., the location they were instructed to reach towards). This feedback proved effective in that subjects were very successful at reaching in the appropriate direction and with the appropriate amplitude (see Section 3).

2.5. Data analysis

Hand position data were smoothed using a fourth-order low-pass Butterworth filter with a cut-off frequency of 14 Hz. Movement onset was defined as the time at which hand speed (i.e., the magnitude of the resultant velocity of the hand) exceeded 10 cm/s and RT was defined as the time period between presentation of the target and the onset of hand movement. The initial direction of the hand was defined as the vector from the start position to the location of the hand 150 ms after movement onset and thus before substantial corrections to the hand trajectory, based on visual feedback, would be observed. Hand direction error (DE) was defined as the angular difference between the initial direction of the hand movement and the required direction of hand movement (i.e., 30, 60 or 180° clockwise from the visual target). For each block of 8 trials, we computed the median DE and RT and all data analyses are based on trial blocks. We used median values as an extra safeguard against outlying or erroneous data points. For statistical tests, an alpha level of 0.05 was considered to be significant.

To quantify adaptation, we fit exponentials of the form $y = ae^{bx} + c$ to the DE adaptation data of each subject. To quantify RT, we first normalized each subject's RTs to their baseline RT. Specifically, for each block we computed ΔRT by subtracting the RT on the final de-adaptation block (block 60) from the RT on that block. Because we expected the use of a strategy to be most likely during early learning [27], we computed, for each subject, the mean ΔRT over blocks 2–11. We excluded the first block because we did not expect increases in RT over the first few reaches.

3. Results

3.1. Adaptation to the 60° visuomotor rotation without RT constraint

Fig. 1A and B show mean hand direction error (DE) and reaction time (RT), averaged across subjects, as a function of trial block in the 60° visuomotor rotation group without RT constraint. Each plot shows data for the 3 practice blocks, the 40 visuomotor rotation blocks (adaptation phase), and the subsequent normal reaching blocks (de-adaptation phase). As expected, the initial DE during the adaptation phase was initially slightly less than the imposed rotation angle, gradually decreased over the first 20 blocks, and leveled out during the last 20 blocks. The DE at the end of the adaptation phase remained elevated. Specifically, the DE in the last adaptation block (block 40) was significantly greater than zero ($t_8 = 3.42$; $p < 0.01$). On average, RT increased from the first to the second block of the adaptation phase, decreased over the next 20 blocks or so, and then leveled out. During the de-adaptation phase, the average DE gradually decreased towards zero and the average RT gradually decreased towards the baseline level seen at the end of the initial practice blocks. Importantly, the average RT remained elevated even at the end of the adaptation phase. A paired *t*-test revealed that RT in the last adaptation block (block 40) was significantly greater ($t_8 = 2.81$; $p = 0.02$) than the RT in the last de-adaptation block (block 60).

The substantial increase in average RT observed during the adaptation phase suggests that at least some subjects may have been using a cognitive strategy to help reduce DE. If so, then we might expect subjects with larger RTs to reduce DE more rapidly. In addition, we would expect subjects with larger RTs to exhibit smaller after-effects. To assess these predictions, we plotted the DE and RT functions for each of the 9 subjects who experienced the 60° visuomotor rotation (Fig. 1C–H). To illustrate the correspondence between DE and RT, we show these subjects' data in three panels. Subjects shown in Fig. 1C and D rapidly decreased DE and exhibited the longest RTs, especially over the first 20 trial blocks. Moreover, DE was decreased close to 0°. In contrast, subjects shown in Fig. 1G and H gradually decreased DE and exhibited the shortest RTs. Indeed, with the exception of a few blocks at the start of the adaptation phase, their RTs were similar to those observed during the normal reaches at the end of the de-adaptation phase. In addition, a substantial steady-state DE was observed at the end of the adaptation phase. Subjects shown in Fig. 1E and F were intermediate between the two other groups in terms of adaptation rate, RT, and steady-state DE. Fig. 1I shows the adaptation exponentials as well as exponentials fit to the DE de-adaptation data. Fig. 1J shows the mean ΔRT over blocks 2–11 and block 40. Note that it is over the initial phase of adaptation that the greatest differences in DE are seen across subjects.