

Contributions of Spatial Working Memory to Visuomotor Learning

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Abstract

■ Previous studies of motor learning have described the importance of cognitive processes during the early stages of learning; however, the precise nature of these processes and their neural correlates remains unclear. The present study investigated whether spatial working memory (SWM) contributes to visuomotor adaptation depending on the stage of learning. We tested the hypothesis that SWM would contribute early in the adaptation process by measuring (i) the correlation between SWM tasks and the rate of adaptation, and (ii) the overlap between the neural substrates of a SWM mental rotation task and visuomotor adaptation. Participants completed a bat-

tery of neuropsychological tests, a visuomotor adaptation task, and an SWM task involving mental rotation, with the latter two tasks performed in a 3.0-T MRI scanner. Performance on a neuropsychological test of SWM (two-dimensional mental rotation) correlated with the rate of early, but not late, visuomotor adaptation. During the early, but not late, adaptation period, participants showed overlapping brain activation with the SWM mental rotation task, in right dorsolateral prefrontal cortex and the bilateral inferior parietal lobules. These findings suggest that the early, but not late, phase of visuomotor adaptation engages SWM processes. ■

INTRODUCTION

Skill learning has been defined as an increase in spatial and temporal accuracy of movements with practice (Willingham, 1998). It is characterized by at least two stages: an initial learning stage (“fast/early learning”), in which within-session improvements can be induced through a limited number of trials on a time scale of minutes (Smith, Ghazizadeh, & Shadmehr, 2006; Puttemans, Wenderoth, & Swinnen, 2005; Karni et al., 1998; Willingham, 1998; Brooks, Hilperath, Brooks, Ross, & Freund, 1995; Brooks, Kennedy, & Ross, 1983; Adams, 1971; Fitts & Posner, 1967), and a “slow/late learning” stage, where improvement occurs incrementally over hours or even days of practice (Doyon, Penhune, & Ungerleider, 2003; Karni et al., 1998; Willingham, 1998). In general, the early learning stage is described as being cognitively demanding, whereas the late learning stage is described as being more automatic (e.g., Fitts & Posner, 1967).

A specific type of skill learning, visuomotor adaptation, has provided important insights into how humans represent and interact with their environment. Visuomotor adaptation requires the modification of a well-learned sensorimotor transformation, based, in part, on neural maps which encode and mediate visuomotor information for use by the motor control system (Cunningham, 1989).¹

There is evidence that modification of these neural maps requires the engagement of cognitive resources for processes such as error encoding and updating visual measurements to motor space (i.e., visuomotor mapping). For example, Taylor and Thoroughman (2007) found that performance of a secondary tone counting task during visuomotor adaptation led to divided attention, which in turn disrupted the encoding of errors during adaptation. Similarly, Eversheim and Bock (2001) found that performing secondary tasks requiring spatial resources, including sensory transformations, interfered with the early phase of adaptation. However, the need for these resources was diminished later in learning, when movement preparation processes were instead called upon to a greater extent. These results indicate that early stages of motor adaptation benefit from the engagement of cognitive resources with other processes playing a greater role later in learning. However, the specific nature of these cognitive contributions remains uncertain.

Consistent with a potential role for cognition in visuomotor adaptation, neuroimaging studies have shown that early learning engages prefrontal brain regions (Anguera, Russell, Noll, & Seidler, 2007; Seidler, Noll, & Chintalapati, 2006; Hikosaka et al., 1999; Sakai et al., 1998; Toni, Krams, Turner, & Passingham, 1998; Inoue et al., 1997; Clower et al., 1996). Although the contribution of prefrontal cortex to adaptation is unknown, the activated site is similar to regions reported in neuroimaging studies of spatial working memory (SWM); more specifically, right prefrontal

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cortex and inferior parietal lobule (Reuter-Lorenz et al., 2000; Courtney, Petit, Maisog, Ungerleider, & Haxby, 1998; McCarthy et al., 1994, 1996; Jonides et al., 1993). One intriguing possibility suggested by this neuroanatomical correspondence is that SWM is engaged during visuomotor adaptation.

Indeed, McNay and Willingham (1998) hypothesized that SWM plays a role in visuomotor adaptation, and the purpose of the present study is to test this idea by examining behavioral and imaging measures of SWM and visuomotor adaptation in the same group of participants. SWM involves the on-line maintenance and active manipulation of spatial information (Miyake & Shah, 1999; Baddeley, 1986). Both behavioral and neural evidence indicates that SWM is dissociable from verbal working memory (Nagel, Ohannessian, & Cummins, 2007; Reuter-Lorenz et al., 2000; Miyake & Shah, 1999), and that individuals differ in SWM capacity (Vogel & Machizawa, 2004; Luck & Vogel, 1997). Furthermore, it has been argued that the storage and processing functions of SWM are essential to mental rotation ability (Suchan, Botko, Gizewski, Forsting, & Daum, 2006; Logie, Della Sala, Beschin, & Denis, 2005; Jordan, Heinze, Lutz, Kanowski, & Jancke, 2001; Cohen et al., 1996), which is the particular application of SWM that may be most relevant to visuomotor adaptation performance.

Seminal work by Just and Carpenter (1976) and Metzler and Shepard (1974) described the following steps thought to underlie mental rotation: the active maintenance of a visual configuration, its transformation, and a subsequent comparison to a target image. These functions require not only SWM but also the more general cognitive processes that several groups have associated with sensorimotor adaptation such as attention (Taylor & Thoroughman, 2007, 2008; Anguera et al., 2007; Seidler et al., 2006; Eversheim & Bock, 2001; McNay & Willingham, 1998). We hypothesize that visuomotor adaptation engages overlapping neural processes related to mental rotation while proceeding through a similar set of steps: understanding that the original visuomotor mapping (where initiated movements directly corresponded with the visual feedback) requires updating to produce accurate movements in this new environment, mentally rotating this neural map with SWM resources, and then using this updated map to perform subsequent movements in the rotated environment.

In the current study, behavioral and neural measures were used to test more precisely the nature and time course of SWM contributions to visuomotor adaptation. Participants performed a joystick-controlled visuomotor adaptation task that required them to make manual aiming movements to targets under veridical and rotated visual feedback in an fMRI environment. Furthermore, they also performed a test of SWM involving mental rotation in the scanner, as well as a battery of neuropsychological assessments of several cognitive processes. We hypothesized that SWM would play a role during early, but not late, adaptation, evidenced by correlations between the

rate of early adaptation and SWM measures, as well as overlapping neural substrates for the performance of SWM and visuomotor adaptation tasks.

METHODS

Participants

Eighteen participants (21.1 ± 2.5 yrs; 9 men) were recruited from the University of Michigan student population and were paid for their participation. Each participant signed an IRB-approved informed consent document and filled out a health history questionnaire prior to the experiment. All participants were right-handed as assessed using the 20-item version of the Edinburgh Inventory (Oldfield, 1971; mean handedness score = 0.83 ± 0.10).

Experimental Setup and Procedure

Testing occurred on two separate days. On Day 1, participants performed a battery of neuropsychological tests to assess the following cognitive processes: (1) mental rotation and spatial relation abilities were tested using Thurston's card rotation (2-D) and cube rotation (3-D) tasks (Ekstrom, French, & Harman, 1976); (2) short-term visuospatial memory was assessed by the forward Corsi Block tapping test (Corsi, 1972); (3) sensorimotor processing speed was determined by the digit-symbol substitution task from WAIS-R (Wechsler, 1997); (4) short-term verbal memory was evaluated by the forward digit span tasks from WAIS-R (Wechsler, 1997) and the reading span task (Daneman & Carpenter, 1980); (5) verbal working memory was assessed by the backward digit span task from WAIS-R (Wechsler, 1997), whereas serial visuospatial working memory was assessed through the backward Corsi Block tapping task (Corsi, 1972); (6) The DEX questionnaire (dysexecutive syndrome; Wilson, Alderman, Burgess, Emslie, & Evans, 1996) is a self-report measure used to determine whether individuals have difficulty with abstract thinking, planning, or other tasks associated with executive functioning. Participants also practiced three blocks of joystick aiming movements made under veridical feedback conditions, as well as one block of an SWM control task (detailed below), to familiarize them with basic task requirements before subsequent testing in the fMRI scanner.

The second day of testing was completed within 1 week of the first testing day. During the second testing session, participants performed the visuomotor adaptation task, the SWM control task (SWMc), and the SWM task which involved mental rotation. For these tasks, participants lay supine in a 3.0-T MRI scanner (General Electric, Waukesha, WI) with their head comfortably restrained to prevent excess head movement. Task presentation and response collection were accomplished with custom LabVIEW 6.1 software (National Instruments, Austin, TX) for the visuomotor adaptation task, and E-Prime 1.1 software for the SWM tasks (Psychology Software Tools, Pittsburgh, PA).

Stimuli were presented through a mirror mounted on a set of specialized goggles, reflecting a video projection screen placed at the rear of the scanner. For the SWM tasks, E-Prime recorded participants' responses ("matching" = thumb press, "different" = index finger) via a right-handed button-glove.

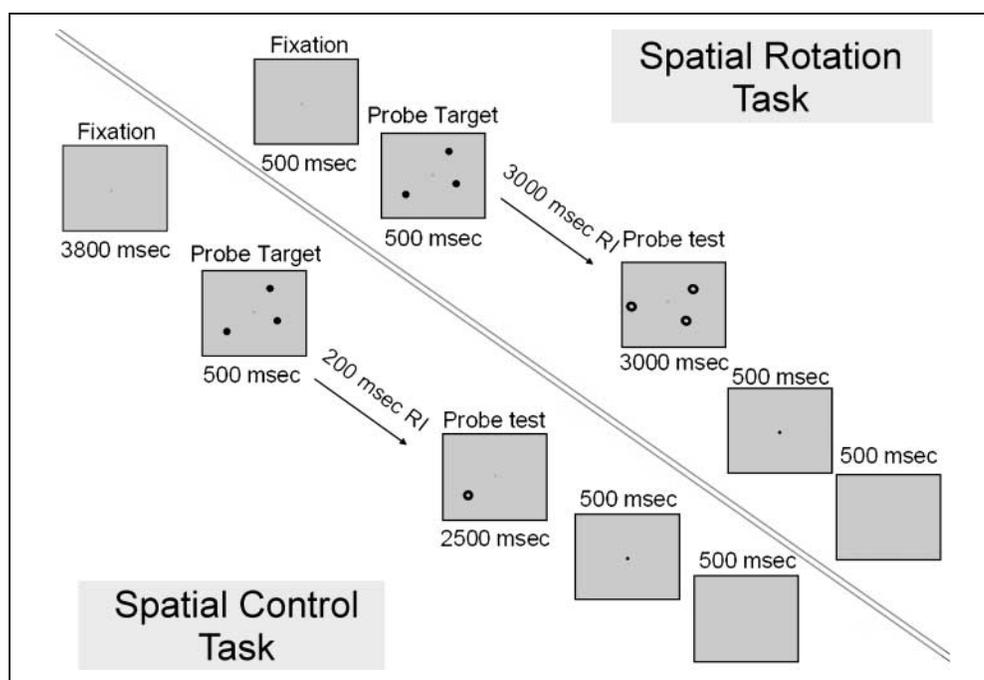
The SWM task, modeled after the task employed by Reuter-Lorenz et al. (2000), required participants to memorize a three-target set (three solid circles) in a 500-msec period (Figure 1). Following presentation of the target set, participants saw a blank screen for 3000 msec (retention interval, RI). During this period, they were instructed to mentally "connect the dots" of the target set, and then mentally rotate this shape by 30° clockwise. Following the RI, participants were given 3000 msec to decide whether the subsequently presented probe set of open circles formed the same configuration as the target set that they had mentally rotated. There was a 30-sec visual fixation baseline period before and after each set of 10 trials. Participants performed two runs of this task, with 30 trials within each run. Seventy percent of the trials were "match" trials in which the probe set was rotated 30° clockwise; the remaining "nonmatch" trials had two of the three probe circles displaced by 1.1 cm (hard), 1.5 cm (medium), and 1.9 cm (easy) from the original target dot configuration.

Participants also performed a SWMc task (1 block of 40 trials; see Figure 1) modeled after the control task used by Reuter-Lorenz et al. (2000). This task involved the presentation of three solid circles for 500 msec, followed by a 200-msec RI; this shortened RI, in theory, requires immediate matching without providing sufficient time to engage working memory processes. Following this, participants were presented with a single circle for 2500 msec and

asked to determine whether its spatial location matched that of a previously observed dot. This control task included all of the cognitive components of the SWM task (e.g., perceptual encoding, response selection, preparation, and initiation), except for the working memory and mental rotation components. Thus, the subtraction of images from the control condition should reveal areas actively involved with SWM and mental rotation (Reuter-Lorenz et al., 2000).

For the visuomotor adaptation task, targets (0.8 cm in diameter) appeared for 4 sec in one of four locations: 4.8 cm to the right, left, above, or below the centrally located home position (0.8 cm in diameter). Participants controlled a cursor with a dual potentiometer joystick placed on their lap. Participants held the joystick with their thumb and index finger, and made small wrist and finger movements to control the joystick, with real-time feedback displayed as a cursor on the projection screen. Participants were asked to move the cursor into the target circle as quickly and accurately as possible, and to maintain the cursor within the circle until the target disappeared. Upon target disappearance, they were told to release the spring-loaded joystick handle so that it would re-center for the subsequent trial. The next trial began 1 sec later, resulting in an intertrial interval (from one target presentation to the next) of 5 sec. Participants performed 13 blocks (B) as separate fMRI runs of the task (24 trials per block), with 30-sec visual fixation baseline periods at the beginning and end of each block. An initial practice block (P) performed in the scanner was not included in the analysis. The first experimental block (B1) was performed under normal visual feedback conditions (control condition), whereas the subsequent 11 blocks (B2–B12; adaptation period) were performed with visual feedback rotated 30° clockwise about the center of the screen.

Figure 1. Spatial rotation (SWM) and spatial control (SWMc) tasks schematic. RI = retention interval.



fMRI Acquisition Parameters

Functional images were acquired using a single-shot, gradient-echo reverse spiral pulse sequence (Börnert, Aldefeld, & Eggers, 2000). The field of view was 220×220 mm, voxel size was $3.2 \times 3.2 \times 3.2$ mm³, TR (repeat time to accomplish a full volume) was 2 sec, and TE (echo time) was 30 msec. Forty contiguous axial slices were acquired, encompassing the whole brain, including the cerebellum. Structural images were acquired using a T1-weighted gradient-echo pulse sequence (TE/TR/FA = 3 msec/250 msec/25°) with a field of view of 240×240 mm and a voxel size of $1.4 \times 1.4 \times 3.2$ mm³.

Behavioral Data Processing

For both the SWMc and SWM task, the response time and percentage of correct responses were calculated. For the adaptation task, the x and y coordinates from the joystick were recorded at a rate of 100 Hz. These data were analyzed off-line using custom LabVIEW 6.1 software (National Instruments) to track behavioral changes with learning. The data were first filtered with a dual low-pass Butterworth digital filter (cf. Winter, 1990), using a cutoff frequency of 10 Hz. The resultant joystick path was calculated by computing the square root of the sum of the squared x and y coordinate data at each time point. The tangential velocity profile was then calculated through differentiation of the resultant position data. Movement onset and offset were computed through the application of Teasdale, Bard, Fleury, Young, and Proteau's (1993) optimal algorithm to the velocity profile for each movement. Learning was assessed by measuring direction error (DE), which is the angle between a straight line from the start to the target position and the position at peak velocity.

We made the assumption based on previous literature that the learning process in visuomotor adaptation contains an "early" and "late" phase (cf. Krebs et al., 1998), with the early phase reflected by a period of rapid improvement, and the late phase showing slower incremental performance gains. To identify which adaptation blocks comprised the early learning period, we searched for the optimal number of consecutive adaptation blocks which resulted in the steepest rate of learning from the first adaptation block (i.e., the slope across the first two adaptation blocks, the slope across the first three adaptation blocks, etc) for each subject. This point was identified as the block whose inclusion led to a significant decrease in the rate of learning slope. Early learning was defined using the most frequently occurring breakpoint in order to keep the number of trials and the amount of practice time consistent across participants. Late learning was then defined as the equivalent consecutive number of adaptation blocks, counting backward from the final adaptation block. Rate of learning was used as the primary adaptation measure. Mean DE was also

examined to provide a within-block index of learning; we performed a Block \times Trial repeated measures analysis of variance (RM ANOVA) on DE to test for differences across blocks and trials. Significant interactions were followed up with simple contrasts. The Huynh and Feldt (1970) epsilon was evaluated to determine whether the repeated measures data met the assumption of sphericity ($\Sigma > 0.75$). Pearson correlations were also computed between performance on each of the neuropsychological tests and accuracy and reaction time for each SWM task, as well as the rate of learning for each adaptation period for DE.

fMRI Data Processing

The first three volumes of each run were discarded to allow the MRI signal to reach its steady state. Head motion correction was performed using the Automated Image Registration package (Woods, Grafton, Holmes, Cherry, & Mazziotta, 1998). Structural images were skull-stripped using FSL's Brain Extraction Tool (www.fmrib.ox.ac.uk/fsl). fMRI data were processed and analyzed using Statistical Parametric Mapping 2 (SPM2; Wellcome Department of Cognitive Neurology, London, UK). We computed a mean functional image for each participant. Then we co-registered the structural image to this mean image and then spatially normalized images to the MNI template (Evans, Kamber, Collins, & Macdonald, 1994). These images were then spatially smoothed with a Gaussian kernel with a full width at half maximum (FWHM) of 8 mm. In addition, head movement parameters were added as covariates of no interest to correct for potential confounding effects induced by head movement.

Boxcar models time-locked to the effect of interest were created and convolved with an estimate of the canonical hemodynamic response function. Analyses were performed at the single participant and group levels through SPM2 to determine regions activated in association with task performance. Significant areas of activation were then localized using the automated anatomical atlas (Tzourio-Mazoyer et al., 2002) and confirmed with the Talairach and Tournoux (1988) atlas. Medial motor areas were identified as in Mayka, Corcos, Leurgans, and Vaillancourt (2006) and Picard and Strick (1996), and cerebellar regions as in Schmahmann et al. (1999).

fMRI Contrasts

Different contrasts were designed to examine the visuomotor adaptation task and the SWM task. The SWM contrast searched for regions of statistically greater activation for the two SWM blocks in comparison to the SWM control block. The first adaptation contrast (*early adaptation*) searched for regions of statistically greater activation across the first three adaptation blocks (defined as the early learning phase by the breakpoint analysis) versus the first

control block (B1). The second adaptation contrast evaluated the late adaptation period using the final three adaptation blocks (*late adaptation*) versus B1. As the neural correlates of SWM, early, and late adaptation have been previously reported in other studies, we utilized a more lenient threshold (p value of .005 and cluster magnitude ≥ 10 voxels) to replicate and display these findings.

In order to evaluate overlapping regions of SWM activation for each task, an inclusive mask of the *SWM contrast* was applied to both the *early* and *late* adaptation activation maps. The threshold for this mask to exclude non-SWM-related voxels was set at a liberal p value of .05, uncorrected; however, all statistical inferences utilized a more stringent false discovery rate-corrected threshold p value of .05 (Genovese, Lazar, & Nichols, 2002). Furthermore, conjunction analyses (using an uncorrected threshold p value of .01, given that each contrast involved had already been subjected to a more stringent threshold; $p < .005$) were also performed to support any mask-related findings and provide evidence of areas being equally engaged during the SWM task and the cor-

responding stage of adaptation. Whole-brain activation correlations were also performed between the following behavioral performance measures and activation at their corresponding scanning blocks: DE early average block score and rate of early adaptation, DE late average block score and rate of late adaptation.

RESULTS

fMRI data from two participants were excluded due to complications with the collection process. This left 18 participants for the behavioral analysis, and 16 for the imaging portion (8 men).

Behavioral Dependent Measures

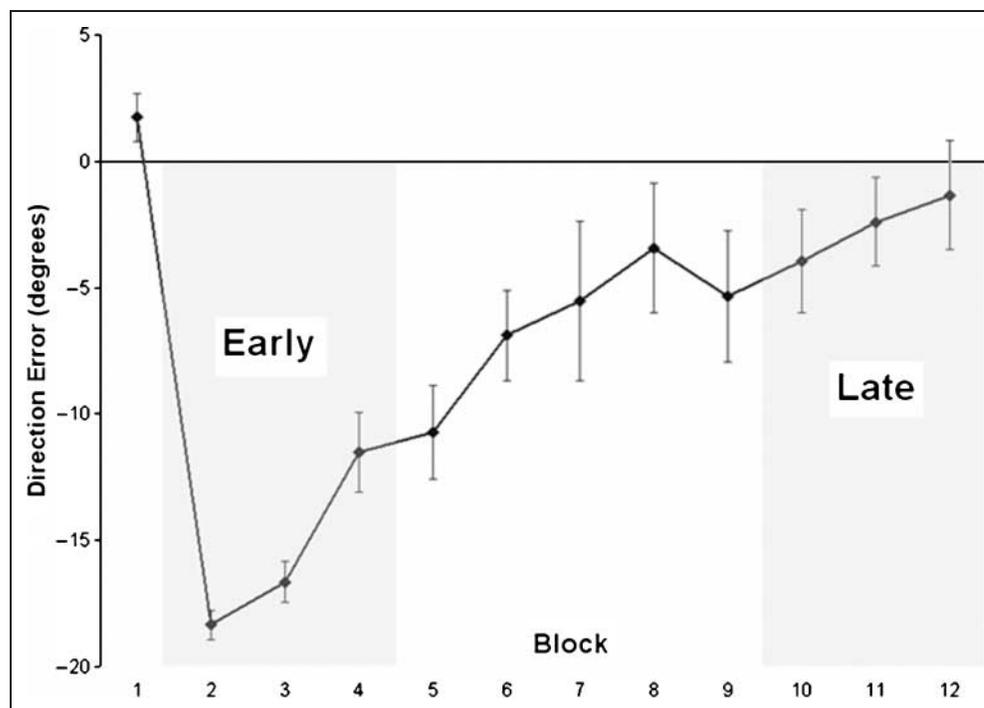
Table 1 shows the group mean and standard deviation for performance on each of the neuropsychological tests, as well as performance on the SWM tasks. As expected, the SWM task was more difficult than the SWMc as indicated

Table 1. Group Mean (M) and Standard Deviation (SD) for Each Behavioral Measure

Task	Units	M	SD
<i>Neuropsychological Test</i>			
Card rotation	# of correct–incorrect cards (3 min)	52.3	20.4
Cube rotation	# of correct–incorrect cubes (3 min)	8.4	6.4
Digit symbol	# of correct symbols (2 min)	79.6	16.2
Corsi forward	# of correct trials	8.7	1.9
Corsi backward	# of correct trials	8.5	1.9
Digit span forward	# of correct trials	11.8	2.6
Digit span backward	# of correct trials	7.8	2.5
Reading span	# of words recalled	30.2	6.3
Edinburgh Inventory	handedness index	.83	.11
DEX	executive impairment	19.8	8.4
<i>SWMc</i>			
Spatial control accuracy	% correct	93%	3%
Spatial control RT	msec	905	147
<i>SWM</i>			
Spatial rotation accuracy	% correct	81%	7%
Spatial rotation RT	msec	1257	209
<i>VMA</i>			
DE (early)	linear slope at early	3.4	1.0
DE (late)	linear slope at late	1.3	0.9

VMA = visuomotor adaptation.

Figure 2. Visuomotor adaptation task performance across all blocks. Each block reflects performance averaged across trials and participants (group mean \pm *SD*). Block 1 was performed under veridical visual feedback, whereas Blocks 2 to 12 were performed under 30° clockwise rotation about the center of the screen.



by lower accuracy [$t(1, 17) = 6.85, p < .0001$] and a longer reaction time [$t(1, 17) = -7.27, p < .0001$].

Figure 2 illustrates performance by block for DE. An RM ANOVA with block (12) and trial (24) for DE resulted in a significant main effect for block [$F(11, 187) = 30.40, p < .0001$], so follow up tests were conducted. Within-participants polynomial contrasts across block for the adaptation period (11 blocks) for each measure showed a significant linear fit [$F(1, 17) = 151.38, p < .001$], indicating improvements with practice. Following the calculation of slopes for each combination of consecutive adaptation blocks, an RM ANOVA with a repeated contrast of the slopes revealed that the first three adaptation blocks had the steepest rate of learning versus all other combinations (see Table 2).

Evidence that the first three adaptation blocks comprised the early adaptation period was established by a difference between the three and four block slopes [$F(1, 17) = 10.49, p < .01$], and leveling off indicated by a lack of difference between the four and five block slopes [$F(1, 17) = .32, p > .50$]. Because the slope across the final eight adaptation blocks and the final three adaptation blocks did not differ [$t(1, 17) = -1.40, p > .15$], we designated the final three adaptation blocks as the late period. Imaging analyses were thus based on an equal number of blocks for the early and late learning periods. Importantly, there was a difference in the three block adaptation slopes between the early and late periods [$t(1, 17) = 7.08, p < .0001$].

Behavioral Correlation Analysis

Table 3 shows the results of the correlation analyses between the neuropsychological tests, measures of accuracy

and RT for the SWM task, and the rate of adaptation for each stage of learning. The card rotation task correlated with both accuracy and RT on the SWM task ($r = .63, p < .05$ and $r = -.52, p < .05$, respectively). The card rotation task also correlated with the DE rate of learning during the early adaptation period ($r = .57, p < .05$; see Figure 3), but not during the late period ($r = -.42, p > .05$; Z-score difference = 3.00, $p < .005$), supporting the hypothesis that SWM processes underlying 2-D mental rotation play a role in early visuomotor adaptation.² The digit symbol task, which tests sensorimotor processing speed, also showed a correlation with the DE rate of learning during the early adaptation

Table 2. Adaptation Slopes for Each Combination of Adaptation Blocks

Adaptation Slope	<i>M</i>	<i>SD</i>
1st 2**	1.71	1.26
1st 3 (11)	3.42	1.03
1st 4** (1)	2.80	0.56
1st 5* (2)	2.88	0.57
1st 6* (2)	2.69	0.47
1st 7**	2.55	0.42
1st 8**	2.13	0.27
1st 9**	1.88	0.20

Each comparison is with regard to the slope for the first three blocks. Numbers in parentheses indicate the number of participants whose adaptation slope was steepest at that particular breakpoint.

* $p < .05$.

** $p < .005$.

Table 3. Behavioral Correlations

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Card rotation	–	–	–	–	–	–	–	–	–	–	–	–	–	–
2. Cube rotation	.52*	–	–	–	–	–	–	–	–	–	–	–	–	–
3. Digit symbol	.49*	.11	–	–	–	–	–	–	–	–	–	–	–	–
4. Corsi forward	.16	.29	–.04	–	–	–	–	–	–	–	–	–	–	–
5. Corsi backward	.13	.22	.22	.68**	–	–	–	–	–	–	–	–	–	–
6. Digit span forward	.08	.11	–.08	.42	.50*	–	–	–	–	–	–	–	–	–
7. Digit span backward	.29	.02	.24	.43	.38	.42	–	–	–	–	–	–	–	–
8. Reading span	.34	.25	–.08	.52*	.50*	.51*	.47	–	–	–	–	–	–	–
9. Edinburgh Inventory	–.41	–.3	–.48*	.35	.29	.33	.02	.01	–	–	–	–	–	–
10. DEX	.29	.18	–.08	.26	–.16	–.20	.05	.25	–.04	–	–	–	–	–
11. Spatial rotation accuracy	.63**	.25	.17	.14	.12	.01	.34	.38	–.01	.16	–	–	–	–
12. Spatial rotation RT	–.52*	–.41	.19	–.14	.08	–.19	–.01	–.30	.20	–.38	–.44	–	–	–
13. DE early slope	.57*	.15	.50*	–.10	–.29	.04	.20	.08	–.43	.44	.29	–.34	–	–
14. DE late slope	–.42	.01	.30	–.22	.02	–.22	–.02	–.41	–.09	–.15	–.43	.45	–.09	–

*Correlation is significant at the .05 level (two-tailed).

**Correlation is significant at the .01 level (two-tailed).

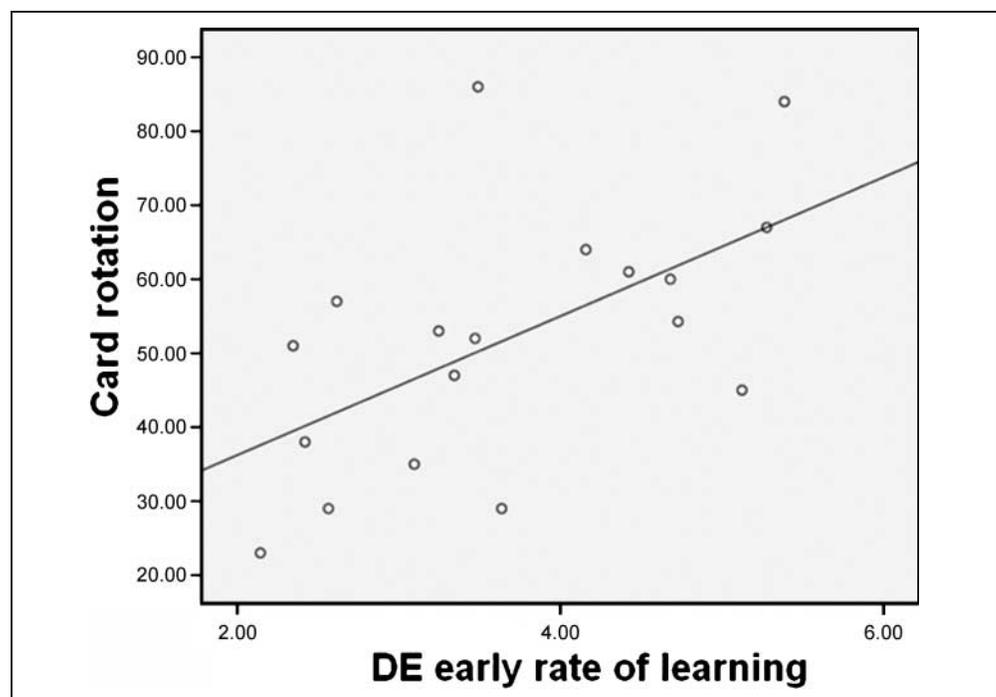
period ($r = .50, p < .05$), but not during the late ($r = .30, p > .05$). Tests of verbal working memory (i.e., forward digit span and reading span) did not show a correlation with the SWM task (forward digit span: $r = .12, p > .05$; reading span: $r = .01, p > .05$), the card rotation task (forward digit span: $r = .08, p > .05$; reading span: $r = .34, p > .05$), or the rate of early learning of the visuomotor adaptation task

(forward digit span: $r = -.29, p > .05$; reading span: $r = .20, p > .05$).

fMRI Results: SWM, Early, and Late Activation

The SWM > SWMc contrast revealed significant bilateral brain activation in a number of frontal, parietal, temporal,

Figure 3. Performance correlation between card rotation task and early adaptation rate of learning, $r = .57, p < .05$.



and cerebellar regions, including right and left DLPFC, consistent with previous investigations of similar tasks (see Table 4; Walter et al., 2003; Nystrom et al., 2000; Reuter-Lorenz et al., 2000; Courtney et al., 1998; McCarthy et al., 1994, 1996; Jonides et al., 1993). Early adaptation was also associated with significant bilateral brain activation in the inferior/middle frontal gyrus (IFG/MFG) and inferior parietal lobule (IPL), in addition to a number of other areas (see Table 5), consistent with previous investigations of visuomotor adaptation (Anguera et al., 2007; Seidler et al., 2006; Hikosaka et al., 1999; Sakai et al., 1998; Toni et al., 1998; Inoue et al., 1997). No regions at late adaptation showed significantly greater activation than the adaptation control condition.³ Using the SWM activation as a limiting mask resulted in early adaptation activation in right DLPFC and bilateral IPL, among other regions (see Table 6 and Figure 4). A conjunction analysis between SWM and early adaptation revealed activation only at right DLPFC (Table 6). There were no regions which reached

Table 4. SWM > SWMc Activation

Anatomic Location	BA	Coordinates of Peak	Z Score
<i>Frontal/Motor</i>			
R IFG	44	48, 6, 28	3.2
L IFG	44	-50, 10, 34	3.7
L DLPFC	46	-48, 34, 18	2.8
R DLPFC	46	38, 36, 14	3.1
<i>Parietal</i>			
R IPL	40	40, -50, 46	2.9
L IPL	40	-34, -56, 44	3.0
R SPL	7	32, -62, 50	2.8
<i>Temporal/Occipital</i>			
R ITG	37	56, -52, 14	2.7
L ITG	37	-44, -56, -6	2.9
L MOG	39	-50, -74, 6	4.2
L SOG	19	-28, -72, 38	3.2
L IOG	18	-40, -88, -10	3.2
R IOG	18	38, -90, -4	3.5
<i>Cerebellum</i>			
R Cerebellum (H V)	-	6, -54, -28	2.7
L Cerebellum (H V)	-	-6, -50, -30	2.7

BA = Brodmann's area; R = right; L = left; IFG = inferior frontal gyrus; DLPFC = dorsolateral prefrontal cortex; IPL = inferior parietal lobule; SPL = superior parietal lobule; ITG = inferior temporal gyrus; MOG = middle occipital gyrus; SOG = superior occipital gyrus; IOG = inferior occipital gyrus; H V = hemisphere 5 of the cerebellum.

Table 5. Early VMA > Control Condition Activation

Anatomic Location	BA	Coordinates of Peak	Z Score
<i>Frontal</i>			
R MFG ^a	9	52, 8, 36	3.5
L IFG ^a	44	-38, 44, 2	3.7
R IFG	47	50, 38, -2	4.4
L IFG ^a	47	-32, 14, -16	3.8
R IFG ^a	46	40, 38, 8	3.6
L MeFG	6	-4, 4, 54	3.4
<i>Motor</i>			
R VPMc	6	48, -4, 32	3.6
R DPMc	6	36, -10, 58	3.6
L DPMc ^a	6	-30, -8, 58	3.1
<i>Parietal</i>			
R IPL ^a	40	54, -42, 43	3.3
L IPL ^a	40	-56, 44, 42	4.0
L SPL ^a	7	-32, -50, 58	3.2
R Prec ^a	7	24, -64, 38	3.7
<i>Others</i>			
R Lingual gyrus	19	22, -56, -8	3.3
L Lingual gyrus	18	-8, -86, 2	4.0
R MTG	21	54, -46, -6	3.4
R Putamen	-	16, 2, 6	4.5
L Putamen	-	-20, 0, 10	4.4
L VL thalamus	-	-18, -16, 12	3.1

BA = Brodmann's area; R = right; L = left; IFG = inferior frontal gyrus; MFG = middle frontal gyrus; MeFG = medial frontal gyrus; VPMc = ventral premotor cortex; DPMc = dorsal premotor cortex; IPL = inferior parietal lobule; SPL = superior parietal lobule; Prec = precuneus; MTG = middle temporal gyrus; VL = ventral lateral.

^aThese regions were also found for the early adaptation > late adaptation contrast.

significance when this mask was applied to the late adaptation period, nor for the conjunction analysis involving these contrasts.

fMRI: Individual Correlations with Whole-brain Activation

Individual differences in activation for each visuomotor adaptation measure at the early and late periods were examined using a whole-brain correlation analysis. Table 7

Table 6. Early Adaptation > Baseline Masked with SWM

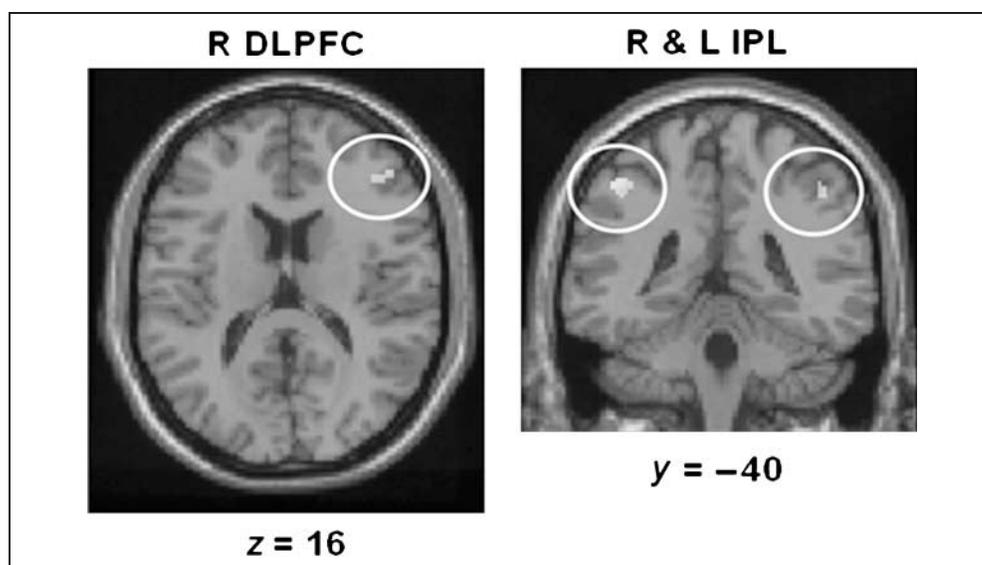
Anatomic Location	BA	Coordinates of Peak	Z Score
<i>Frontal/Motor</i>			
R LPMC	6	52, 8, 36	3.6
R IFG	46	40, 38, 10	3.4
R DLPFC	46	46, 40, 16	3.4
R DLPFC ^a	46	42, 34, 14	2.7
<i>Parietal</i>			
R IPL	40	48, -40, 44	3.2
L IPL	40	-46, -38, 50	4.1
R Prec	22	22, -72, 50	3.4
L SPL	7	-32, -50, 58	3.9
R SOG	19	24, -64, 38	3.9

BA = Brodmann's area; R = right; L = left; IFG = inferior frontal gyrus; DLPFC = dorsolateral prefrontal cortex; LPMC = lateral premotor cortex; IPL = inferior parietal lobule; SPL = superior parietal lobule; Prec = precuneus; SOG = superior occipital gyrus.

^aConjunction: early adaptation > baseline and SWM > SWMc contrasts.

shows activation in the left MFG/DLPFC and caudate obtained from a whole-brain correlation analysis of early visuomotor activation with the rate (slope) of early adaptation. Using the same analysis with the rate of late adaptation resulted in activation in the left middle temporal gyrus, left superior temporal gyrus, as well as the left cerebellum (H IX; Table 7). Right precuneus and superior parietal lobule activation was observed when the early mean DE score was correlated with early adaptation activation (Table 7).

Figure 4. These images present activation from Table 7. The left image ($z = 16$) depicts activation in right dorsolateral prefrontal cortex (R DLPFC). The right image ($y = -40$) depicts activity at the left and right inferior parietal lobule (IPL). Left in this image corresponds to participant's left.



DISCUSSION

The present study tested the hypothesis that SWM contributes to visuomotor adaptation, with the results supporting the proposal that early, but not late, adaptation engages SWM. Support for this proposal was evidenced by the findings that: (i) individual differences on Thurston's card rotation task predicted the rate of early but not late adaptation, and (ii) brain activation associated with the SWM mental rotation task overlapped with that of the early, but not late, adaptation period. Despite recent assertions that this task is largely implicit (Mazzoni & Krakauer, 2006), these findings are consistent with the hypothesis that SWM processes are involved in the early stages of acquiring new visuomotor mappings.

Correlations between Cognitive Measures and Visuomotor Adaptation

In agreement with previous studies of visuomotor adaptation (Anguera et al., 2007; Seidler et al., 2006; Smith et al., 2006; Krakauer et al., 2004; Ghilardi et al., 2000; Cunningham, 1989), as well as motor learning theories (Doyon et al., 2003; Willingham, 1998), more rapid improvement was observed at the early adaptation stage than the late adaptation stage. Furthermore, the finding that the rate of early, but not late, visuomotor adaptation correlates with the card rotation task and the digit symbol task suggests distinct cognitive contributions to the early stages of learning. This pattern is also consistent with less cognitive and more "automatic" influences in later learning (Taylor & Thoroughman, 2007, 2008; Eversheim & Bock, 2001; Karni et al., 1998; Adams, 1971; Fitts & Posner, 1967). In addition, there were no correlations between the early or late rate of adaptation and

Table 7. Correlations with Whole-brain Activation

Anatomic Location	BA	Coordinates of Peak	Z Score
<i>Parietal</i>			
R Prec ^a	7	4, -56, 58	3.2
R SPL ^a	7	24, -48, 64	2.7
<i>Temporal</i>			
L MTG ^b	21	-48, -48, 6	3.5
L STG ^b	22	-46, -34, 14	3.3
L STG ^a	28	-26, 8, -22	3.0
<i>Others</i>			
L MFG/DLPFC ^c	45/46	-52, 32, 16	3.1
L Cerebellum (H IV) ^a		-18, -28, -28	3.2
L Cerebellum (H IX) ^b		-14, -58, -44	3.3
L Caudate ^c		-8, 8, 4	3.2
L Hippo ^a		-34, -28, -8	3.3

BA = Brodmann's area; R = right; L = left; Prec = precuneus; SPL = superior parietal lobule; MTG = middle temporal gyrus; STG = superior temporal gyrus; MFG = middle frontal gyrus; DLPFC = dorsolateral prefrontal cortex; H VI = hemisphere 6 of the cerebellum; IX = hemisphere 9 of the cerebellum; Hippo = hippocampus.

^aDE average early score with first three adapt blocks activation.

^bDE late slope correlation with final three adaptation blocks activation.

^cDE early slope correlation with first three adaptation blocks activation.

verbal working memory measures (i.e., digit span, reading span), suggesting that the observed correlations do not reflect a general executive effect. It is important to note that all of the reported correlations no longer reach significance after correcting for multiple comparisons ($p < .0005$). However, one could argue that because certain correlations were predicted a priori (e.g., the card rotation rate of early adaptation, card rotation–SWM accuracy), a post hoc correction for significance could be considered unnecessary. Regardless, the strength of these correlations is modest and these findings should be replicated with larger samples in the future.

The selectivity of the correlations between our neuropsychological measures and early adaptation performance is consistent with the idea that specific cognitive operations contribute to motor learning (see also Bock, 2005). That is, the significant correlation between card rotation and early adaptation suggests that 2-D rotation ability may be a critical shared process, whereas the lack of correlation with backward Corsi block and cube rotation argues that neither general SWM abilities nor 3-D rotation ability are significantly related to visuomotor adaptation. Although this interpretation suggests that the observed correlation results are both task- and environment-dependent, a clear behavioral distinction between these

working memory resources has not been observed (Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001; Carroll, 1993; Lohman, 1988). A concern with the present study is that we did not find a significant correlation between SWM accuracy (fMRI task) and the rate of early learning. This result was unexpected, given (i) the card rotation/SWM task accuracy correlation, and (ii) the card rotation/rate of early adaptation correlation. Although it is unclear why this correlation was nonsignificant, the significant correlations between the card rotation task, and the cube and SWM tasks do support that these tasks share similar processes related to mental rotation.

The early visuomotor adaptation period, the card rotation task, and the SWM task all require “active” SWM (involving manipulation and transformation) as opposed to “passive” SWM (involving maintenance and/or comparison). The null correlations between the rate of early adaptation and (i) the cube rotation task, or (ii) the Corsi backward task suggest that the type of SWM process utilized may be specific to the task at hand. We speculate that a spatial n -back task would not show a correlation with adaptation due to the absence of the mental rotation component. Furthermore, it may be that learning a visuomotor adaptation in 3-D space would correlate with a 3-D mental rotation task (i.e., cube rotation). One may question whether the observed relationship between visuomotor adaptation and SWM is task-specific, or whether SWM plays a role in other motor learning tasks as well. We have recently shown that visuospatial working memory capacity predicts the organization of explicitly acquired motor sequences (Bo & Seidler, 2009), supporting the possibility that the current findings may generalize to other motor tasks.

SWM, Early, and Late Activation

Activation associated with the SWM > SWMc contrast was observed bilaterally in the IFG/MFG and IPL, including right DLPFC. These findings are in accord with other imaging studies of SWM and mental rotation (Milivojevic, Hamm, & Corballis, 2009; Suchan et al., 2006; Walter et al., 2003; Gauthier et al., 2002; Nystrom et al., 2000; Reuter-Lorenz et al., 2000; Courtney et al., 1998; Cohen et al., 1996; McCarthy et al., 1994, 1996; Jonides et al., 1993). The observed activation in premotor, prefrontal, temporal, and parietal regions during the early adaptation phase also agrees with previous imaging studies of visuomotor adaptation (Anguera et al., 2007; Seidler et al., 2006; Krakauer et al., 2004; Clower et al., 1996). No regions reached significance at late learning, an outcome which also agrees with prior studies of this and similar tasks.

It is important to note that the early and late learning periods were defined relative to a total learning duration of approximately 40 min. Thus, it is unclear whether our findings would generalize to visuomotor adaptation that spans multiple days or learning sessions (Della-Maggiore & McIntosh, 2005; Graydon, Friston, Thomas, Brooks, &

Menon, 2005). Regardless of the length or number of sessions, an exact breakpoint between early and late learning processes is less likely than a gradual transition occurring from one to the other.

Neural Overlap between SWM and Visuomotor Adaptation

When both the early and late adaptation periods were masked with the activation from the SWM task, only the early adaptation period showed significant activation. In particular, right DLPFC and bilateral IPL, regions which have previously been associated with mental rotation in SWM tasks (Suchan et al., 2006; Jordan et al., 2001; Gill, O'Boyle, & Hathaway, 1998), were engaged. The overlapping engagement of right DLPFC for the SWM task and early adaptation period was supported by the conjunction analysis. In addition, masked overlapping activation was also observed in the right IFG and right PMC, supporting previous work from this laboratory which suggested that these right-lateralized regions comprise a network that contributes to spatial cognitive processes of adaptation, specifically SWM and spatial attention (Seidler et al., 2006). Other studies have also reported right-lateralized activation with the same visuomotor adaptation task (Krakauer et al., 2004; Ghilardi et al., 2000; Inoue et al., 1997), but have not interpreted this activation as supporting SWM processes.

The present findings suggest that prefrontal activation during the early stage of adaptation reflects engagement of SWM processes underlying mental rotation. These data support previous work suggesting that cognitive processes play a role in the adaptation process (Taylor & Thoroughman, 2007, 2008; Eversheim & Bock, 2001), and are also in line with theories of motor learning regarding the engagement of distinct neural correlates at different stages of learning (Smith et al., 2006; Doyon et al., 2003; Willingham, 1998).

Neural Correlates of Visuomotor Adaptation

There was a correlation between the rate of early adaptation and activation in the left MFG/DLPFC. This region was also active in the SWM contrast, indirectly supporting the function of SWM processes during early adaptation. During late learning, left middle temporal gyrus activation was correlated with the rate of late adaptation. Activation in this region was previously observed during late learning for a sensorimotor adaptation task (Krebs et al., 1998). Individual mean early DE score correlated with activation at the right precuneus and superior parietal lobule, both regions we have previously observed during the early adaptation period for this task (Anguera et al., 2007; Seidler et al., 2006).

Unfortunately, the design of the present study prevented discerning strategic on-line corrections from gradual visuomotor recalibration, both of which have been

shown to influence sensorimotor adaptation. However, strategic control is quickly engaged following awareness of the altered visuomotor mapping, with recalibration occurring over an extended period of exposure to the perturbation (cf. Richards, Mulavara, & Bloomberg, 2007). This transition to a more autonomous stage is reflected by a shift in activation away from prefrontal cortex toward regions such as the cerebellum, which is hypothesized to reflect the storage and refinement of the new internal model for this task (Seidler & Noll, 2008; Graydon et al., 2005; Imamizu et al., 2000). In the present study, cerebellar activation (H IX), but not prefrontal activity, correlated with the rate of late adaptation, supporting this interpretation.

How Is SWM Used in the Motor Learning Process?

How does SWM contribute to visuomotor adaptation? We propose that it is recruited to support mental rotation used to modify visuomotor maps. We suggest that the learner recalls the original, congruent visuomotor map, mentally rotates this map with SWM resources, and then uses this updated map to plan the subsequent movement in the rotated environment. Although the maintenance of error information in WM likely contributes to the adaptation process, we believe the manipulation of the contents in WM for a given trial is critical for adaptation to take place. This interpretation agrees with Abeele and Bock's (2001) proposal that adaptation progresses in a gradual fashion across the learning period from small angles of transformation through intermediate values until the prescribed angle of rotation is reached. Thus, the engagement of these SWM resources late in adaptation is markedly diminished, as compared to early adaptation, when the new mapping has been formed and is in use. These proposals also agree with electrophysiological data demonstrating an interaction between motor areas and a fronto-parietal network for information processing in motor adaptation (Wise, Moody, Blomstrom, & Mitz, 1998). It should be noted that other cognitive processes such as error detection and monitoring (Anguera, Seidler, & Gehring, 2009) are also likely contributing to the early phase of visuomotor adaptation.

Recent dual-tasking studies of motor adaptation and executive function have provided a framework for when SWM would most likely be recruited during the early adaptation period. Taylor and Thoroughman (2007, 2008) have shown that the adaptation process is most affected when attentional resources are distracted by a secondary task imposed late in the trial, when error information becomes available. These authors suggest that cognitive resources are engaged between trials so that error information can be integrated to update visuomotor maps for the subsequent trial, because a secondary task performed early in the trial did not produce interference. Direct testing of this theory was not possible in the current study due to the use of a block design to image the visuomotor adaptation task. Nevertheless, our findings are consistent with the

idea that participants are utilizing SWM to transform their motor plan for subsequent trials based on information held in WM comparing performance between previous accurate and current deviated movements.

Conclusion

The early, but not late, stage of visuomotor adaptation is related to SWM processes. This relationship was evidenced by behavioral performance correlations and by overlapping neural activation patterns between early stages of adaptation and a SWM task involving mental rotation. These findings point to a role for spatial cognition early in the motor learning process, and provide insight into the potential functions served by prefrontal and parietal regions that are selectively engaged during the visuomotor adaptation process.

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Notes

1. The terms learning and adaptation each describe a relatively enduring change in performance, with adaptation being more relevant to the present study. The phrase “neural map” describes the central nervous system’s correspondence, or mapping, between observed movements encoded visually and direction of movement as incorporated into motor commands for the hand–arm system (Cunningham & Welch, 1994), with “visuomotor map” being specific to the task in the present study.
2. Fitts and Posner’s (1967) theory of skill learning also included an intermediate stage, where aspects of both early and late learning were present. Although considerable change in performance occurred during the “intermediate stage” of the current study, the rate of learning during this period (B5–B9) did not correlate with any of the neuropsychological measures ($p > .05$ in each case), suggesting distinct neural processes were utilized here (vs. early learning).
3. Another approach to measuring adaptation is a direct contrast of the early and late adaptation periods. The early > late adaptation contrast revealed comparable frontal and parietal regions of activation to the early > control contrast (noted in Table 5), whereas the late > early contrast did not result in any significant activation. These findings provide further support of the early adaptation period selectively utilizing SWM regions.

REFERENCES

Abeele, S., & Bock, O. (2001). Mechanisms for sensorimotor adaptation to rotated visual input. *Experimental Brain Research*, *139*, 248–253.

- Adams, J. A. (1971). A closed-loop theory of motor learning. *Journal of Motor Behavior*, *3*, 111–149.
- Anguera, J. A., Russell, C. A., Noll, D. C., & Seidler, R. D. (2007). Neural correlates associated with intermanual transfer of sensorimotor adaptation. *Brain Research*, *1185*, 136–151.
- Anguera, J. A., Seidler, R. D., & Gehring, W. J. (2009). Changes in performance monitoring during sensorimotor adaptation. *Journal of Neurophysiology*, *102*, 1868–1879.
- Baddeley, A. (1986). *Working memory*. Oxford: Oxford University Press.
- Bo, J., & Seidler, R. D. (2009). Visuospatial working memory capacity predicts the organization of acquired explicit motor sequences. *Journal of Neurophysiology*, *101*, 3116–3125.
- Bock, O. (2005). Components of sensorimotor adaptation in young and elderly subjects. *Experimental Brain Research*, *160*, 259–263.
- Börnert, P., Aldefeld, B., & Eggers, H. (2000). Reversed spiral MR imaging. *Magnetic Resonance in Medicine*, *44*, 479–484.
- Brooks, V., Hilperath, F., Brooks, M., Ross, H. G., & Freund, H. J. (1995). Learning “what” and “how” in a human motor task. *Learning and Memory*, *2*, 225–242.
- Brooks, V. B., Kennedy, P. R., & Ross, H. G. (1983). Movement programming depends on understanding of behavioral requirements. *Physiology & Behavior*, *31*, 561–563.
- Carroll, J. (1993). *Human cognitive abilities: A survey of factor-analytic studies*. New York: Cambridge University Press.
- Clower, D. M., Hoffman, J. M., Votaw, J. R., Faber, T. L., Woods, R. P., & Alexander, G. E. (1996). Role of posterior parietal cortex in the recalibration of visually guided reaching. *Nature*, *383*, 618–621.
- Cohen, M. S., Kosslyn, S. M., Breiter, H. C., DiGirolamo, G. J., Thompson, W. L., Anderson, A. K., et al. (1996). Changes in cortical activity during mental rotation. A mapping study using functional MRI. *Brain*, *119*, 89–100.
- Corsi, P. (1972). *Human memory and the medial temporal region of the brain* (Vol. 34 (02), 819B). University Microfilms (AA105-77717).
- Courtney, S. M., Petit, L., Maisog, J. M., Ungerleider, L. G., & Haxby, J. V. (1998). An area specialized for spatial working memory in human frontal cortex. *Science*, *279*, 1347–1351.
- Cunningham, H. A. (1989). Aiming error under transformed spatial mappings suggests a structure for visual–motor maps. *Journal of Experimental Psychology: Human Perception and Performance*, *15*, 493–506.
- Cunningham, H. A., & Welch, R. B. (1994). Multiple concurrent visual–motor mappings: Implications for models of adaptation. *Journal of Experimental Psychology: Human Perception and Performance*, *20*, 987–999.
- Daneman, M., & Carpenter, P. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Behavior*, *19*, 450–466.
- Della-Maggiore, V., & McIntosh, A. R. (2005). Time course of changes in brain activity and functional connectivity associated with long-term adaptation to a rotational transformation. *Journal of Neurophysiology*, *93*, 2254–2262.
- Doyon, J., Penhune, V., & Ungerleider, L. G. (2003). Distinct contribution of the cortico-striatal and cortico-cerebellar systems to motor skill learning. *Neuropsychologia*, *41*, 252–262.
- Ekstrom, R., French, J., & Harman, H. (1976). *Manual for kit of factor referenced cognitive tests*. Princeton, NJ: Educational Testing Service.
- Evans, A., Kamber, M., Collins, D., & Macdonald, D. (1994). An MRI-based probabilistic atlas of neuroanatomy. In S. Shorvon, D. Fish, F. Andermann, G. Bydder, & H. Stefan (Eds.), *Magnetic resonance scanning and epilepsy*. NATO ASI Series A, *Life Sciences* (Vol. 264, pp. 263–274). New York: Plenum.

- Eversheim, U., & Bock, O. (2001). Evidence for processing stages in skill acquisition: A dual-task study. *Learning and Memory*, *8*, 183–189.
- Fitts, P. M., & Posner, M. I. (1967). *Human performance*. Belmont, CA: Brooks/Cole Publishing.
- Gauthier, I., Hayward, W. G., Tarr, M. J., Anderson, A. W., Skudlarski, P., & Gore, J. C. (2002). BOLD activity during mental rotation and viewpoint-dependent object recognition. *Neuron*, *34*, 161–171.
- Genovese, C. R., Lazar, N. A., & Nichols, T. (2002). Thresholding of statistical maps in functional neuroimaging using the false discovery rate. *Neuroimage*, *15*, 870–878.
- Ghilardi, M., Ghez, C., Dhawan, V., Moeller, J., Mentis, M., Nakamura, T., et al. (2000). Patterns of regional brain activation associated with different forms of motor learning. *Brain Research*, *871*, 127–145.
- Gill, H. S., O'Boyle, M. W., & Hathaway, J. (1998). Cortical distribution of EEG activity for component processes during mental rotation. *Cortex*, *34*, 707–718.
- Graydon, F. X., Friston, K. J., Thomas, C. G., Brooks, V. B., & Menon, R. S. (2005). Learning-related fMRI activation associated with a rotational visuo-motor transformation. *Brain Research, Cognitive Brain Research*, *22*, 373–383.
- Hikosaka, O., Nakahara, H., Rand, M. K., Sakai, K., Lu, X., Nakamura, K., et al. (1999). Parallel neural networks for learning sequential procedures. *Trends in Neurosciences*, *22*, 464–471.
- Huynh, H., & Feldt, L. (1970). Conditions under which the mean square ratios in repeated measures designs have exact F-distributions. *Journal of the American Statistical Association*, *65*, 1582–1589.
- Imamizu, H., Miyauchi, S., Tamada, T., Sasaki, Y., Takino, R., Pütz, B., et al. (2000). Human cerebellar activity reflecting an acquired internal model of a new tool. *Nature*, *403*, 192–195.
- Inoue, K., Kawashima, R., Satoh, K., Kinomura, S., Goto, R., Sugiura, M., et al. (1997). Activity in the parietal area during visuomotor learning with optical rotation. *NeuroReport*, *8*, 3979–3983.
- Jonides, J., Smith, E. E., Koeppe, R. A., Awh, E., Minoshima, S., & Mintun, M. A. (1993). Spatial working memory in humans as revealed by PET. *Nature*, *363*, 623–625.
- Jordan, K., Heinze, H. J., Lutz, K., Kanowski, M., & Jancke, L. (2001). Cortical activations during the mental rotation of different visual objects. *Neuroimage*, *13*, 143–152.
- Just, A., & Carpenter, P. (1976). Eye fixations and cognitive processes. *Cognitive Psychology*, *8*, 441–480.
- Karni, A., Meyer, G., Rey-Hipolito, C., Jezzard, P., Adams, M. M., Turner, R., et al. (1998). The acquisition of skilled motor performance: Fast and slow experience-driven changes in primary motor cortex. *Proceedings of the National Academy of Sciences, U.S.A.*, *95*, 861–868.
- Krakauer, J. W., Ghilardi, M. F., Mentis, M., Barnes, A., Veysman, M., Eidelberg, D., et al. (2004). Differential cortical and subcortical activations in learning rotations and gains for reaching: A PET study. *Journal of Neurophysiology*, *91*, 924–933.
- Krebs, H. I., Brashers-Krug, T., Rauch, S. L., Savage, C. R., Hogan, N., Rubin, R. H., et al. (1998). Robot-aided functional imaging: Application to a motor learning study. *Human Brain Mapping*, *6*, 59–72.
- Logie, R. H., Della Sala, S., Beschin, N., & Denis, M. (2005). Dissociating mental transformations and visuo-spatial storage in working memory: Evidence from representational neglect. *Memory*, *13*, 430–434.
- Lohman, D. (Ed.) (1988). *Spatial abilities as traits, processes and knowledge* (Vol. 4). Hillsdale, NJ: Erlbaum.
- Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature*, *390*, 279–281.
- Mayka, M. A., Corcos, D. M., Leurgans, S. E., & Vaillancourt, D. E. (2006). Three-dimensional locations and boundaries of motor and premotor cortices as defined by functional brain imaging: A meta-analysis. *Neuroimage*, *31*, 1453–1474.
- Mazzoni, P., & Krakauer, J. W. (2006). An implicit plan overrides an explicit strategy during visuomotor adaptation. *Journal of Neuroscience*, *26*, 3642–3645.
- McCarthy, G., Blamire, A. M., Puce, A., Nobre, A. C., Bloch, G., Hyder, F., et al. (1994). Functional magnetic-resonance-imaging of human prefrontal cortex activation during a spatial working-memory task. *Proceedings of the National Academy of Sciences, U.S.A.*, *91*, 8690–8694.
- McCarthy, G., Puce, A., Constable, R. T., Krystal, J. H., Gore, J. C., & Goldman-Rakic, P. (1996). Activation of human prefrontal cortex during spatial and nonspatial working memory tasks measured by functional MRI. *Cerebral Cortex*, *6*, 600–611.
- McNay, E. C., & Willingham, D. B. (1998). Deficit in learning of a motor skill requiring strategy, but not of perceptuomotor recalibration, with aging. *Learning and Memory*, *4*, 411–420.
- Metzler, J., & Shepard, R. (Eds.) (1974). *Transformational studies of the internal representation of three dimensional objects*. Potomac, MD: Erlbaum.
- Milivojevic, B., Hamm, J. P., & Corballis, M. C. (2009). Functional neuroanatomy of mental rotation. *Journal of Cognitive Neuroscience*, *21*, 945–959.
- Miyake, A., Friedman, N. P., Rettinger, D. A., Shah, P., & Hegarty, M. (2001). How are visuospatial working memory, executive functioning, and spatial abilities related? A latent-variable analysis. *Journal of Experimental Psychology: General*, *130*, 621–640.
- Miyake, A., & Shah, P. (Eds.) (1999). *Models of working memory: Mechanisms of active maintenance and executive control*. New York: Cambridge University Press.
- Nagel, B. J., Ohannessian, A., & Cummins, K. (2007). Performance dissociation during verbal and spatial working memory tasks. *Perceptual & Motor Skills*, *105*, 243–250.
- Nystrom, L. E., Braver, T. S., Sabb, F. W., Delgado, M. R., Noll, D. C., & Cohen, J. D. (2000). Working memory for letters, shapes, and locations: fMRI evidence against stimulus-based regional organization in human prefrontal cortex. *Neuroimage*, *11*, 424–446.
- Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, *9*, 97–113.
- Picard, N., & Strick, P. L. (1996). Motor areas of the medial wall: A review of their location and functional activation. *Cerebral Cortex*, *6*, 342–353.
- Puttemans, V., Wenderoth, N., & Swinnen, S. P. (2005). Changes in brain activation during the acquisition of a multifrequency bimanual coordination task: From the cognitive stage to advanced levels of automaticity. *Journal of Neuroscience*, *25*, 4270–4278.
- Reuter-Lorenz, P. A., Jonides, J., Smith, E. E., Hartley, A., Miller, A., Marshuetz, C., et al. (2000). Age differences in the frontal lateralization of verbal and spatial working memory revealed by PET. *Journal of Cognitive Neuroscience*, *12*, 174–187.
- Richards, J. T., Mulavara, A. P., & Bloomberg, J. J. (2007). The interplay between strategic and adaptive control mechanisms in plastic recalibration of locomotor function. *Experimental Brain Research*, *178*, 326–338.
- Sakai, K., Hikosaka, O., Miyauchi, S., Takino, R., Sasaki, Y., & Pütz, B. (1998). Transition of brain activation from frontal to parietal areas in visuomotor sequence learning. *Journal of Neuroscience*, *18*, 1827–1840.
- Schmahmann, J. D., Doyon, J., McDonald, D., Holmes, C., Lavoie, K., Hurwitz, A. S., et al. (1999). Three-dimensional

- MRI atlas of the human cerebellum in proportional stereotaxic space. *Neuroimage*, *10*, 233–260.
- Seidler, R. D., & Noll, D. C. (2008). Neuroanatomical correlates of motor acquisition and motor transfer. *Journal of Neurophysiology*, *99*, 1836–1845.
- Seidler, R. D., Noll, D. C., & Chintalapati, P. (2006). Bilateral basal ganglia activation associated with sensorimotor adaptation. *Experimental Brain Research*, *175*, 544–555.
- Smith, M. A., Ghazizadeh, A., & Shadmehr, R. (2006). Interacting adaptive processes with different timescales underlie short-term motor learning. *PLoS Biology*, *4*, e179.
- Suchan, B., Botko, R., Gizewski, E., Forsting, M., & Daum, I. (2006). Neural substrates of manipulation in visuospatial working memory. *Neuroscience*, *139*, 351–357.
- Talairach, J., & Tournoux, P. (1988). *Co-planar stereotaxic atlas of the human brain. 3-Dimensional proportional system, an approach to cerebral imaging* (M. Rayport, Trans.). New York: Thieme.
- Taylor, J. A., & Thoroughman, K. A. (2007). Divided attention impairs human motor adaptation but not feedback control. *Journal of Neurophysiology*, *98*, 317–326.
- Taylor, J. A., & Thoroughman, K. A. (2008). Motor adaptation scaled by the difficulty of a secondary cognitive task. *PLoS ONE*, *3*, e2485.
- Teasdale, N., Bard, C., Fleury, M., Young, D. E., & Proteau, L. (1993). Determining movement onsets from temporal series. *Journal of Motor Behavior*, *25*, 97–106.
- Toni, I., Krams, M., Turner, R., & Passingham, R. E. (1998). The time course of changes during motor sequence learning: A whole-brain fMRI study. *Neuroimage*, *8*, 50–61.
- Tzourio-Mazoyer, N., Landeau, B., Papathanassiou, D., Crivello, F., Etard, O., Delcroix, N., et al. (2002). Automated anatomical labeling of activations in SPM using a macroscopic anatomical parcellation of the MNI MRI single-subject brain. *Neuroimage*, *15*, 273–289.
- Vogel, E. K., & Machizawa, M. G. (2004). Neural activity predicts individual differences in visual working memory capacity. *Nature*, *428*, 748–751.
- Walter, H., Bretschneider, V., Gron, G., Zurowski, B., Wunderlich, A. P., Tomczak, R., et al. (2003). Evidence for quantitative domain dominance for verbal and spatial working memory in frontal and parietal cortex. *Cortex*, *39*, 897–911.
- Wechsler, D. (1997). *Wechsler Adult Intelligence Scale* (3rd ed.). San Antonio, TX: Psychological Corporation.
- Willingham, D. B. (1998). A neuropsychological theory of motor skill learning. *Psychological Review*, *105*, 558–584.
- Wilson, B., Alderman, N., Burgess, P., Emslie, H., & Evans, J. (1996). *Behavioural assessment of the dysexecutive syndrome*. Bury St. Edmunds, UK: Thames Valley Test Company.
- Winter, D. (1990). *Biomechanics and motor control of human movement* (2nd ed.). New York: Wiley.
- Wise, S. P., Moody, S. L., Blomstrom, K. J., & Mitz, A. R. (1998). Changes in motor cortical activity during visuomotor adaptation. *Experimental Brain Research*, *121*, 285–299.
- Woods, R. P., Grafton, S. T., Holmes, C. J., Cherry, S. R., & Mazziotta, J. C. (1998). Automated image registration: I. General methods and intrasubject, intramodality validation. *Journal of Computer Assisted Tomography*, *22*, 139–152.