Performance Benefits Associated With Context-dependent Arm Pointing Adaptation*

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Abstract

Our previous work has demonstrated that head orientation can be used as a contextual cue to switch between multiple adaptive states. Subjects were assigned to one of three groups: the head orientation group tilted the head towards the right shoulder when drawing under a 0.5 gain of display and towards the left shoulder when drawing under a 1.5 gain of display; the target orientation group had the home & target positions rotated counterclockwise when drawing under the 0.5 gain and clockwise for the 1.5 gain; the arm posture group changed the elbow angle of the arm they were not drawing with from full flexion to full extension with 0.5 and 1.5 gain display changes. The head orientation cue was effectively associated with the multiple gains, in comparison to the control conditions. The purpose of the current investigation was to determine whether this context-dependent adaptation results in any savings in terms of performance measures such as movement duration and movement smoothness when subjects switch between multiple adaptive states. Subjects in the head adaptation group demonstrated reduced movement duration and increased movement smoothness (measured via normalized jerk scores) in comparison to the two control groups when switching between the 0.5 and 1.5 gain of display. This work has demonstrated not only that subjects can acquire context-dependent adaptation, but also that it results in a significant savings of performance upon transfer between adaptive states.

Introduction

Recent work has demonstrated that subjects can concurrently store two or more visuomotor maps by alternately switching back and forth between environments over blocks of trials [4, 5, 7, 17, 29]. Following repeated exposures, subjects require fewer trials to re-adapt and exhibit reduced aftereffects each time they switch between exposures. This has been demonstrated with a variety of adaptive stimuli, including wedge prisms [5,17,29], rotated visual feedback [4], varying VOR gains [23, 24, 26], and force fields perturbing the direction of limb movement [8]. Additionally, some investigations have demonstrated that subjects are able to associate contextual cues with either multiple VOR gains (Shelhamer et al., 23, 24) or multiple adaptive force states (Gandolfo et al., 18), minimizing the cost of switching among environments. Thus, when the subject is presented with the specific contextual condition, he or she is able to automatically perform using the appropriate acquired adaptive state. For example, Shelhamer and colleagues (23, 24) examined whether head postures could be associated with multiple gains of the vestibulo ocular reflex (VOR). They exposed subjects to alternating periods of VOR gain, shifting the head orientation with each change in gain (head tilted in roll or pitch). After successive exposures, subjects were able to anticipate a new VOR gain automatically when the head orientation was changed. In another example, Gandolfo et al. [8] had subjects adapt to a force field opposing their movement, with force magnitude proportional to the velocity of the moving limb. Subjects alternated between a clockwise- and a counter clockwise-directed opposing force field. Two types of stimuli were used as contextual cue conditions to aid subjects in switching between the two states. The first was color; the room was flooded with one color light for the clockwise field and another for the counter clockwise field. This was not effective, however, in enabling the subjects to switch from one state to another.

The other type of contextual cue condition was the hand posture used to grasp the manipulandum. One posture was with the hand halfway between full pronation and full supination, and the other was fully pronated, effectively changing the muscle requirements to move the manipulandum. The use of these different postures was sufficient to enable subjects to switch automatically between the two mappings.

From the above data it appears that contextual cues that are effectively associated with multiple adaptive states are those that are intrinsic to the task. This interpretation would explain the effectiveness of hand posture for arm pointing adaptation in the Gandolfo et al. [8] study and head orientation for VOR adaptation observed by Shelhamer and colleagues [23, 24, 26]. Our recent work (Seidler et al., in review) has confirmed that cues which are an integral aspect of task performance are more effectively associated with the acquired adaptation. In this study, subjects alternated between drawing under 0.5 and 1.5 gain of display conditions. Three subject groups participated, each receiving a different contextual cue: the head orientation group tilted the head towards the right shoulder when drawing under the 0.5 gain of display and towards the left shoulder when drawing under the 1.5 gain of display; the target orientation group had the home & target positions rotated counterclockwise when drawing under the 0.5 gain and clockwise for the 1.5 gain; the arm posture group changed the elbow angle of the arm they were not drawing with from full flexion to full extension with 0.5 and 1.5 gain display changes. When returning to drawing under the 1.0 gain, subjects in the head orientation group exhibited aftereffects that were appropriate for the contextual cues that they had trained with. These data provide support for the idea that static head orientation information is a crucial component to the arm adaptation process, and that effective contextual cues are those that are an integral aspect of task performance.

The use of contextual cues appears to eliminate the need for consolidation time (Shadmehr & Brashers-Krug, 21, 22) before subjects switch between states. The discovery of any contextual cue that aids subjects in switching between multiple adaptive states is of clear benefit to adaptive training programs. For example, the appropriate context could be used to help astronauts switch between multiple adaptive sets, a set appropriate for microgravity, the partial gravity environment of Mars, and the unit gravity environment of Earth. The subjects would merely need to train in association with a contextual cue (or cues). Effective adaptive training could help to mitigate the performance declines occurring upon microgravity exposure and return to normal gravity such as impaired postural control, reduced eye-head coordination, and slower, less accurate pointing movements (Berger et al., 1995; Watt, 1997; Black et al., 1995).

In order to fully appreciate the benefits of the use of contextual cues it is important to understand how they impact all aspects of performance. In addition to determining whether contextual cues can be effectively associated with acquired adaptations, it is important to determine the "savings" associated with the cue. Therefore, the purpose of this study was to analyze movement performance when subjects acquire dual adaptive states using various contextual cues to determine whether cue association is accompanied by enhanced performance. Using the data from Seidler et al. (in review), we assessed motor performance measures such as movement time and movement fluency (measured via normalized jerk score). We predicted that the head orientation contextual cue group would show enhanced performance (i.e., smoother, faster movements) in comparison to the two control groups (arm posture and target orientation) after associating head orientation with the appropriate adaptive state. Portions of these data have been published previously (Seidler et al., in review).

Methods

Subjects. Three groups of twelve subjects were recruited from the Arizona State University campus to participate. Group 1 subjects (4 males, 8 females) were 24.8 (sd=4.5) years old; group 2 subjects (6 males, 6 females) were 25.7 (sd=4.2) years old, and group 3 subjects (4 males, 8 females) were 25.2 (sd=4.3) years old. After hearing an explanation of the experiment the subjects decided whether they wanted to volunteer. If they did, they provided written informed consent in accordance with human subjects' policies. Subjects were compensated with extra credit for an undergraduate motor learning course for their participation, which took an average of one hour. An additional four subjects per group were recruited to participate in a second experiment, aimed at determining how the strength of cue association increases over repeated exposures to visuomotor conflict. These subjects received twice the amount of adaptation training in comparison to Experiment 1 subjects.

Procedure. Subjects were seated in front of a computer monitor, with their arm resting on a digitizing tablet. The shoulder was flexed to 90° for the starting posture, and the table height was adjusted to support the arm in a posture parallel to the floor. The head was fixed to a support for the duration of the experiment. Subjects grasped the stylus in a whole hand grasp to prevent them from making adjustments to the pen position with their fingers. Subjects wore goggles that were blacked out on the lower half to prevent vision of the moving hand. The subjects performed aiming movements to various targets on a Wacom digitizer. Custom software was used to present the imperative stimulus (auditory go signal), the targets, and the pen trace, and to collect the x and y pen tip coordinates at 206 Hz during the course of the movements. Targets were displayed on a 30 cm by 40 cm monitor, placed at eye level 60 cm back from the subjects' eyes. The subjects were instructed to perform the movements as rapidly and as accurately as possible upon an auditory go signal. Although latency of response was not stressed, anticipation and no response trials were omitted by having subjects repeat trials in which they did not achieve a reaction time (RT) between 100 ms and 1000 ms. All other trials were retained, regardless of whether or not the target was achieved.

Subjects were randomly assigned to one of three groups, each receiving a different cue condition: 1) subjects changed static head posture from +20° of roll to -20° of roll with the gain of display changing from 1.5 to 0.5, 2) the target orientation was changed by tilting the computer monitor from +20° to -20° of roll with the gain changing from 1.5 to 0.5 and the head remaining fixed, 3) the left arm posture varied from full elbow extension to full elbow flexion while again the gain changed from 1.5 to 0.5.

All three groups performed a pre test with the gain of display at 1.0 (20 trials), an adaptation block in which the gain of display alternated between 0.5 and 1.5 every 20 trials for three successive sets (120 trials total), and a post test (32 trials) in which the gain was returned to 1.0 (see Table 1 for an overview of trial presentation). The 0.5 gain of display requires subjects to travel twice the distance on the tablet compared to the distance displayed on the monitor, and the 1.5 gain of display requires subjects to travel three quarters of the distance on the tablet compared to the displayed pen trace. During the adaptation block, the level of cue was changed with every gain change (i.e., head orientation went from +20° to -20° of roll, target orientation and arm posture changed in a similar fashion). Cue levels and corresponding gains of display are presented in Table 1.

To examine whether there was any interference between cue effectiveness and recency effects arising from the last gain experienced during the adaptation block, the groups were subdivided into two. One half of the subjects received one cue level for the first portion of the post test (for example, +20° of head roll, which was associated with the 0.5 gain during adaptation) and the other received the remaining cue level (for example, -20° of head roll, which was associated with the 1.5 gain during adaptation). The level of cue was changed halfway through the post test (at 16 trials) to determine whether the direction of aftereffect changed accordingly with the gain that had been previously associated with the level of cue during the adaptation block. Subjects participating in the second, smaller experiment (four subjects for each of the three cue groups) followed the same protocol except that they performed the adaptation block two times (240 total adaptation trials) before continuing on to the post test.

Data Analysis. The position data were subjected to a residual analysis in order to determine the appropriate cutoff frequency for data filtering [31]; the resulting value used was 7 Hz. The resultant path was computed by taking the square root of the sum of the squared x and y coordinate data. The tangential speed and acceleration profiles were then found by successive differentiation. The optimal algorithm of Teasdale, Bard, Fleury, Young, and Proteau [25] was used to determine movement onset from the velocity profiles. The algorithm works as follows: Locate the sample at which the velocity time series first exceeds 10% of its maximum value (Vmax); working back from this point stop at the first sample (call it S) less than or equal to (Vmax/10)-(Vmax/100); find the standard deviation of the series between sample 1 and sample S (call this sd); working back from S stop at the first sample less than or equal to S-sd; this is the onset sample. As sampling was terminated when subjects remained stationary for 300 ms, the same algorithm was used in reverse to determine movement offset.

Subjects typically perform movement corrections during adaptation experiments, evident as corrective submovements in the velocity profile [14, 18], especially towards the beginning of the adaptation blocks when they are learning the task and adapting to the change in the gain of display. Since the focus of interest was more in how the subjects preplanned the movements and less in the on-line corrections that they made, we decomposed the movement into its primary and secondary submovements. The primary submovement is thought to be mostly under ballistic control whereas the secondary submovement reflects a feedback-based correction [18]. The existence of secondary submovements was determined using an algorithm that searches for a positive acceleration value following a period of deceleration, or a change in the sign of the velocity, signifying a change in movement direction. The end of the primary submovement was also considered the beginning of the secondary submovement. While it is acknowledged that multiple corrective submovements may occur, they were considered as one corrective phase for the purposes of this analysis. Trials not containing corrective submovements were excluded from mean calculations of secondary submovement amplitude and duration (i. e., rather than entering values of 0.0 cm amplitude and 0 ms duration).

Using these methods of submovement decomposition allowed us to portion the movement into ballistic and corrective phases. This enabled us to compute the distance covered in the primary submovement. This variable is reflective of programming errors rather than errors in any feedback-based corrections. For example, the primary submovement should cover approximately 50% of the total distance for the initial trials of the 0.5 gain of display adaptation blocks and 150% of the total distance for the initial trials of the 1.5 gain blocks.

Additional variables were computed in order to determine the performance savings that occurred when subjects associated adaptive states with contextual cues. These variables were total movement duration, primary submovement duration, secondary submovement duration, and normalized jerk score. Movement smoothness was assessed by calculating the jerk score for the pen trajectory and normalizing it for the distance and duration as follows:

(1) $\mathrm{sqrt}(1/2 \cdot \int j^2(t)\,dt \cdot d^5/l^2)$,

where j is the third time derivative of the position data, d is the movement duration, and l is the movement amplitude. The value is thus unit-free, normalized for the amplitude and duration of the movement.

A within subjects MANOVA (group × block × trial) with repeated measures on trial and block was used to determine how performance varied across each block. The Huynh-Feldt epsilon [13] was evaluated to determine whether the repeated measures data met the assumption of sphericity ($\Sigma > .75$). In cases where sphericity was met, the univariate tests were used to maintain power. Otherwise, the repeated measures were treated as multivariate. Note that the significance of the F value is assessed using different degrees of freedom depending on whether the univariate or multivariate tests are used. An effect size measure, _^{2}, was computed for all variables. It is an estimate of the total population variance that is explained by the variation due to the treatment [15]. Its value does not depend on sample size or power of the experiment. Its values can range between 0.0 and 1.0, with negative values a possibility when the associated F value is less than 1.0. Cohen suggests that a small effect is comparable to an ω^2 of .01, a medium effect is .06, and a large effect is .15 or greater [3]. These standards were employed in our assessment of treatment effect sizes. Data analyses for the second experiment were identical, except that the majority of the interpretation focused on the effect sizes rather than the p values since only four subjects per group participated.

Results

The primary submovement distance data were reported previously (Seidler et al., in review); these data demonstrated that head orientation can be effectively associated with adaptive states, while arm posture and target orientation are not (Seidler et al., in review).

Portions of this data will be presented here again (Figures 1-3) in order to allow comparison to the performance variables (primary, secondary, and total movement duration, and normalized jerk score). The proportion of the total distance covered in the primary submovement did not differ across groups for the subjects who performed 120 adaptation trials (Figure 1A, quadratic trends across trials due to the gain changes are evident, but they do not vary by group). Some group differences began to emerge, however, for the subjects that performed 240 adaptation trials. The performance disruptions occurring due to gain changes were diminished across the second set of six adaptation blocks for the head posture group, resulting in group x trial interactions for some of these blocks (Figure 1B, second set of adaptation trials performed, only the first five trials are plotted to increase clarity of the initial group separations). Although the interactions were not always statistically significant (which was not surprising given the small number of subjects participating), the effect sizes were moderate to large. These occurred in the odd-numbered blocks only (0.5 gain of display Blocks numbered 1, 3, 5. Effect sizes ranged ω^2=.18-.40, large effect sizes, with both head posture and target orientation groups differing from the arm posture cue group). There were no group differences in the quadratic trends across trials in the even-numbered adaptation blocks, in which the gain was 1.5 (trial main effects, Blocks 2, 4, 6. Effect sizes ranged ω^2=.65-.81, large effect size).

Figures 2 and 3 present the post test data for the subjects who performed 120 and 240 adaptation trials, respectively. The groups are split by condition (level of cue) for these plots, as there were significant effects involving condition during the post-test. It can be seen from these two figures that the head posture contextual cue group consistently demonstrated aftereffects that corresponded to the gain these subjects had experienced during adaptation (effect sizes ranged from _^{2}=.11-.47, medium to large effect sizes). That is, subjects in condition 1 overshot the target for the first portion of the post test and undershot for the second portion, while condition 2 subjects presented the opposite effects.

There are two approaches that can be utilized to determine whether the context-dependent adaptation observed in the head posture group is associated with enhanced performance. One method is to assess whether this group demonstrated faster, smoother movements towards the end of adaptation, when the subjects began exhibiting a reduced impact upon changing gains (i.e., Figure 1B trials). The other is to analyze the post-test movements, when the head posture group demonstrated aftereffects, to determine if they were moving more slowly and less fluently. Both approaches were utilized.

As can be seen in Figure 1B, there were group differences in the distance covered in the primary submovement during the second set of adaptation trials for subjects participating in Experiment 2. This was not associated with group differences in total and primary submovement duration for these subjects. It can be seen, however, that the head posture subjects spent a smaller amount of time in the secondary submovement than the other two groups in blocks 1, 3, and 5 of the second set of adaptation trials (_^{2}=.16, .02, .42, respectively; values were negative for blocks 2, 4, 6, Figure 4A). Note that these are the same blocks in which the head posture subjects exhibit a reduced response to changing gains (Figure 1B). Moreover, this group moved more smoothly than the other two groups throughout this set of adaptation trials (Figure 4B, _^{2}=.03, small effect size).

The Experiment 1 subjects demonstrated a group x block x condition interaction for the post test primary submovement duration (Figure 5B, $F_{2,30}$=6.2, p<.01, _^{2}=.13, medium effect size). The head posture subjects in condition 1 spent a greater amount of time in the primary submovement in block 1 than those subjects in condition 2. This was not true for the other groups, nor was it true for the second block. Although not significant, there was a clear trend for this effect in the total movement time data as well (Figure 5A). There were no effects for secondary submovement duration and normalized jerk score for these subjects.

Group x condition interactions were observed for both total movement duration and primary submovement duration for the Experiment 2 post tests (Figure 6A and 6B, respectively. Total movement time $F_{2,7}$=7.2, p=.03, _^{2}=.15, large effect size. Primary submovement time $F_{2,7}$=4.8, p=.05, _^{2}=.10, medium effect size). It can be observed in the figures (6A and 6B) that the head posture group subjects in condition one had greater movement durations than those subjects in condition two for the first post test block, associated with the aftereffects observed in Figure 3. The target orientation group tended to show the same effect, although the condition separation was not as large. There were no significant effects obtained for the secondary submovement duration and the normalized jerk scores.

Discussion

Previously we demonstrated that head posture is consistently effective as a contextual cue to aid subjects in switching among multiple gains, in comparison to arm posture and target orientation contextual cues (Seidler et al., in review). This likely occurs due to a functional linkage between head and arm control, making head orientation an integral aspect of arm movement control. With the present analyses, we have demonstrated that this association not only allows subjects to maintain accurate pointing performance when switching between environments, but also enables them to maintain fast, smooth trajectories as well. The implications for adaptive training programs are strong: the use of contextual cues during acquisition of multiple adaptive states can reduce or eliminate the time required to re-adapt when switching between environments, it can eliminate consolidation time, and it can help subjects to maintain rapid, accurate, and smooth performance.

It is unclear how the head posture contextual cue enables subjects to switch between adaptive states. It could potentially facilitate priming of the appropriate visuomotor map and/or simultaneously inhibit the competing mappings. Shadmehr and Holcomb [22] have demonstrated that a learned pattern needs to be inhibited before acquisition of a competing pattern can occur. Their work suggests that this process requires consolidation time (5.5 hr was sufficient for their task) and involves the ventral prefrontal cortex [22]. The data presented in the current experiment suggest that appropriate cues can expedite this process.

When an astronaut enters space, he or she typically requires a few days to adapt to the microgravity environment and its sensory consequences (Kornilova, 1997). The astronaut must adapt to impairments in sensorimotor integration and orientation illusions (Clement et al., 1987; Reschke et al., 1994). These impairments can produce marked decrements in postural control (Black et al., 1995) and eye-head coordination (Kornilova et al., 1991; Oman et al., 1990) upon return to Earth, that gradually fade over a period of approximately one week for shorter duration flights (Black et al., 1995). Berger and colleagues (1995) have reported profound increases in movement duration in-flight, ranging from 33-50%, when subjects perform ballistic movements to a target. Additionally, Watt and colleagues (Watt et al., 1985; Watt, 1997) have reported increases in endpoint errors, particularly when subjects point to remembered target locations, in-flight and post-flight, with respect to their pre-flight performance (Watt et al., 1985). Thus, there is a need for adaptive training to mitigate performance decrements occurring both upon initial exposure to microgravity and upon return to Earth. Thus, a thorough understanding of adaptive mechanisms and the potential benefits of adaptive training with contextual cues is required to enhance performance by reducing adaptation (and re-adaptation) time.

The results reported here have significant implications for the design of adaptive training programs. They contribute to a cohesive theory regarding the effectiveness of contextual cues to aid switching between multiple adaptive states; it appears that effective cues are those that are an integral aspect of the task. Moreover, we have demonstrated that association of adaptive states with contextual cues results in faster, smoother, and more accurate movement performance.

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Table 1

Trial Descriptions

Block Number	Arm Posture Cue Group	Target Orientation Cue Group	Head Orientation Cue Group
Block 1. Pre Test	10 trials right-to-left, 10 trials left-to-right, 8.0 cm, gain = 1.0, neutral arm posture.	10 trials right-to-left, 10 trials left-to-right, 8.0 cm, gain = 1.0, neutral monitor position.	10 trials right-to-left, 10 trials left-to-right, 8.0 cm, gain = 1.0, neutral head orientation.
Block 2. Adaptation			
A1:	20 trials 16.0 cm, gain = 0.5, non-dominant arm in full flexion.	20 trials 16.0 cm, gain = 0.5, monitor in +20° roll.	20 trials 16.0 cm, gain = 0.5, head in +20° roll.
A2:	20 trials 5.3 cm, gain = 1.5, non-dominant arm in full extension.	20 trials 5.3 cm, gain = 1.5, monitor in -20° roll.	20 trials 5.3 cm, gain = 1.5, head in -20° roll.
A3:	Identical to A1.	Identical to A1.	Identical to A1.
A4:	Identical to A2.	Identical to A2.	Identical to A2.
A5:	Identical to A1,3.	Identical to A1,3.	Identical to A1,3.
A6:	Identical to A2,4.	Identical to A2,4.	Identical to A2,4.
Block 3. Post Test	32 trials, 8.0 cm, gain = 1.0, non-dominant arm flexed first 16 trials, extended last 16 trials (half subjects extension first, flexion second).	32 trials, 8.0 cm, gain = 1.0, monitor in +20° roll first 16 trials, -20° roll last 16 trials (half subjects +20° first, -20° second).	32 trials, 8.0 cm, gain = 1.0, head in +20° roll first 16 trials, -20° roll last 16 trials (half subjects +20° first, -20° second).

Figure Captions

1. Primary submovement distance across the adaptation blocks for Experiment 1 (upper row) and the second half of Experiment 2 (lower row). Block numbers are defined in Table 1; the first half of each block consists of leftward movements while the second half are rightward movements. There were significant linear and quadratic trends across trials in each block as subjects adapted performance to the altered gain of display within each block. Only the first five trials of each block are presented for the Experiment 2 data. There were large effect sizes for the group x trial interaction in blocks A1, A3, and A5 of the second set of adaptation blocks (lower row). In these blocks, the head posture group exhibiting a lessening of performance disruptions upon switching between the two gains of display.
2. Experiment 1 post-test primary submovement distance (1.0 gain of display, plotted by level of cue). The upper row plots the first 16 trials and the lower row plots the second 16 (following the change in cue level). The target orientation group exhibited a cue effect for the first post-test block, while the head posture group exhibited a trend for a cue effect for the first post-test block and a significant cue effect for the second post-test block.
3. Experiment Two post-test primary submovement distance (1.0 gain of display, plotted by level of cue). The upper row plots the first 16 trials and the lower row plots the second 16 (following the change in cue level). There were large condition effect sizes, with the head posture cue effective for both the first and second post blocks and the target orientation cue effective for the second post test block only.
4. Panel A depicts secondary submovement duration for the Experiment 2 subjects, during the second half of the adaptation trials. Note that the head posture group spends less time in the secondary submovement for the same blocks in which they demonstrate greater primary

submovement distance in Figure 1 (blocks 1, 3, 5). Panel B depicts normalized jerk score, in which the head posture group subjects demonstrate smoother movements than the arm posture and target orientation subjects across the entire block.

5. Panel A depicts total movement duration for the Experiment 1 subjects during the post test. Although not significant, there was a clear trend for the head posture subjects in condition 1 to exhibit greater movement durations than those subjects in condition 2. Panel B depicts primary submovement duration. The head posture subjects in condition 1 spent a greater amount of time in the primary submovement in block 1 than those subjects in condition 2. This was not true for the other groups, nor was it true for the second block.

<u>6.</u> Panel A depicts total movement duration for the Experiment 2 subjects during the post test; Panel B depicts primary submovement duration. It can be observed in both figures that the head posture group subjects in condition one had greater movement durations than those subjects in condition two for the first post test block, associated with the aftereffects observed in Figure 3. The target orientation group tended to show the same effect.

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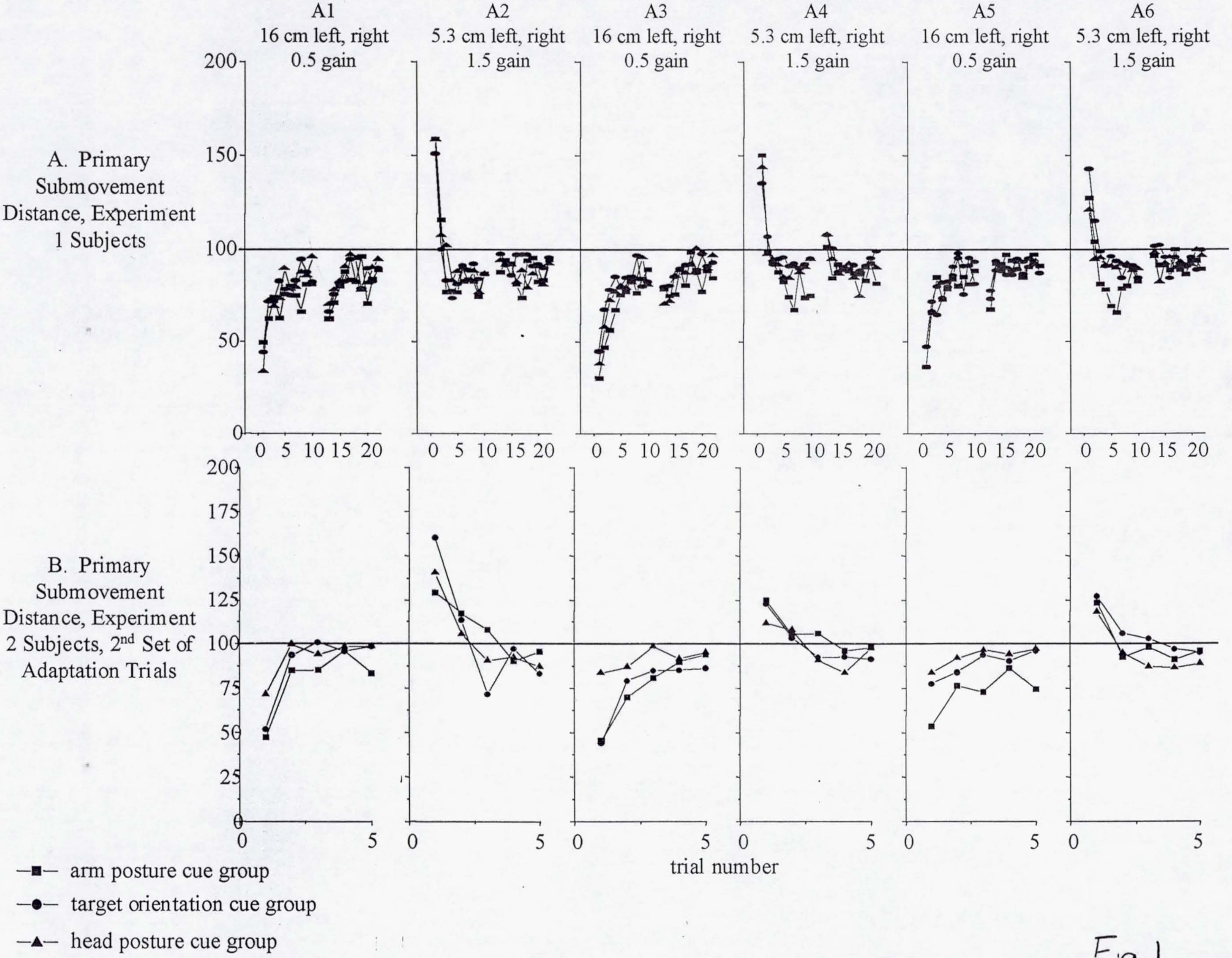

A1
16 cm left, right
0.5 gain
A2
5.3 cm left, right
1.5 gain
A3
16 cm left, right
0.5 gain
A4
5.3 cm left, right
1.5 gain
A5
16 cm left, right
0.5 gain
A6
5.3 cm left, right
1.5 gain
A. Primary Submovement Distance, Experiment 1 Subjects
200
150
100
50
0
0 5 10 15 20
B. Primary Submovement Distance, Experiment 2 Subjects, 2nd Set of Adaptation Trials
200
175
150
125
100
75
50
25
0
0
5
trial number
—■— arm posture cue group
—●— target orientation cue group
—▲— head posture cue group

Fig. 1

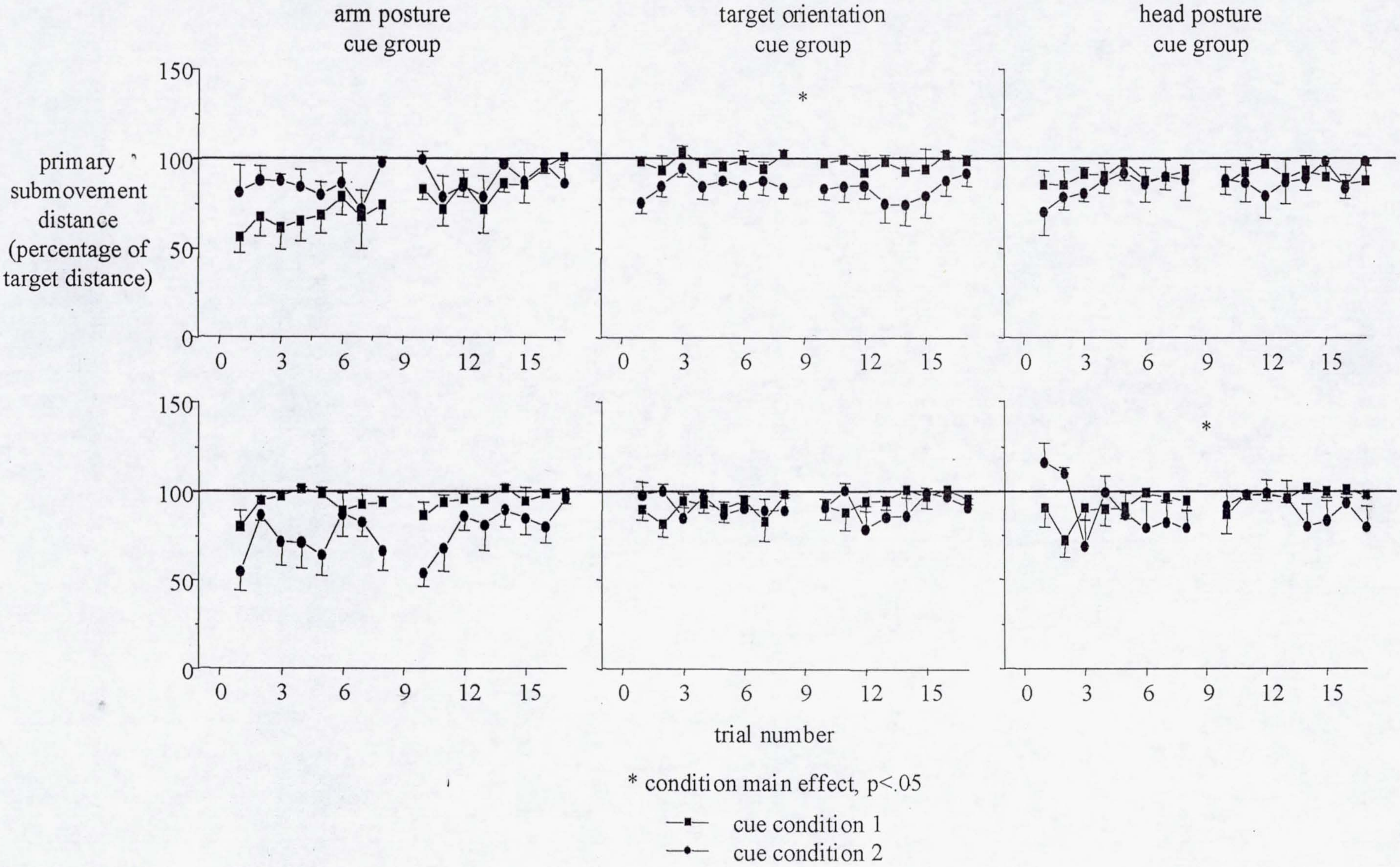

arm posture cue group
target orientation cue group
head posture cue group
primary submovement distance (percentage of target distance)
150
100
50
0
0
3
6
9
12
15
*
trial number
* condition main effect, p<.05
cue condition 1
cue condition 2

Fig.2

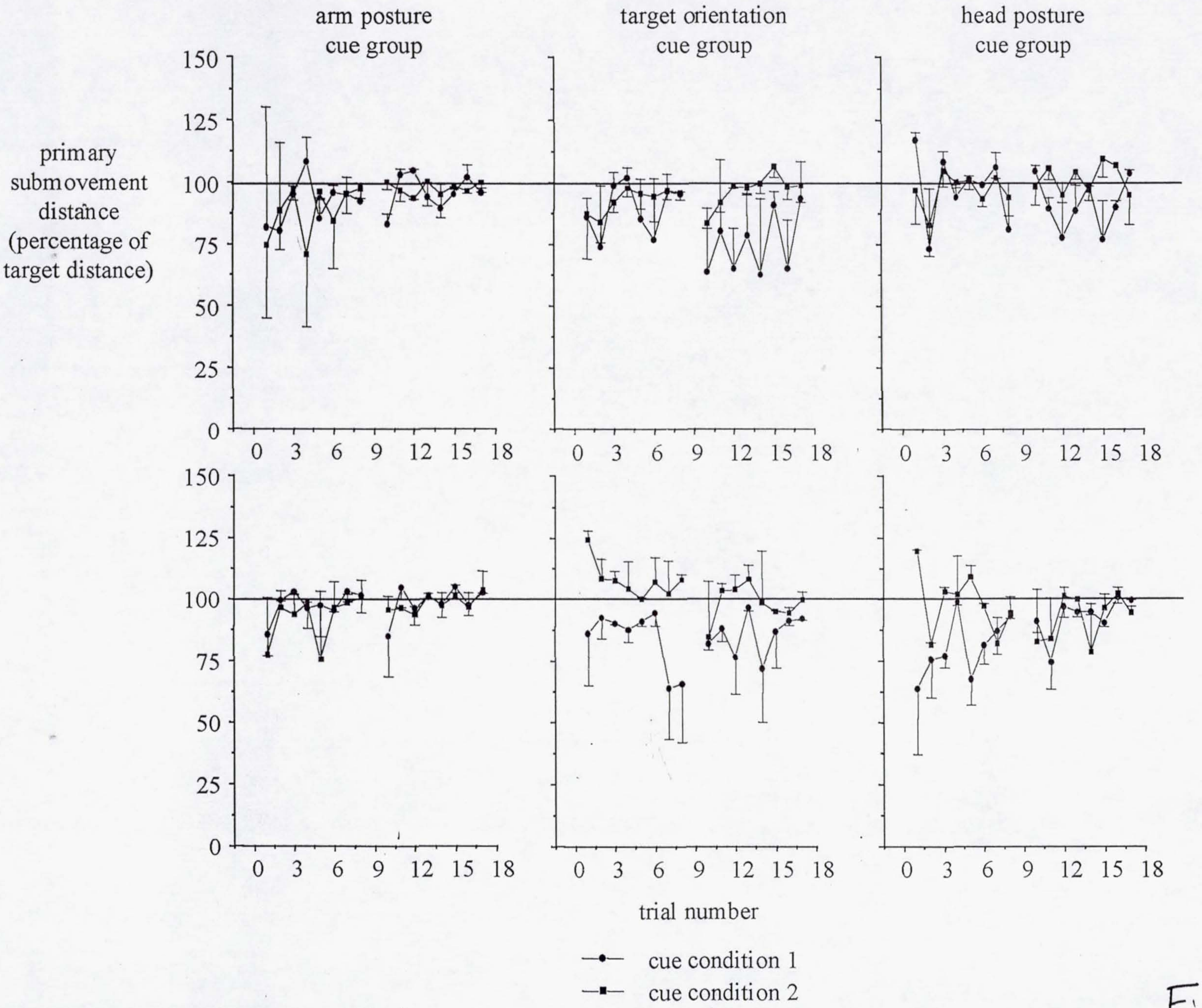

arm posture cue group
target orientation cue group
head posture cue group
primary submovement distance (percentage of target distance)
150
125
100
75
50
25
0
0 3 6 9 12 15 18
trial number
cue condition 1
cue condition 2

Fig. 3

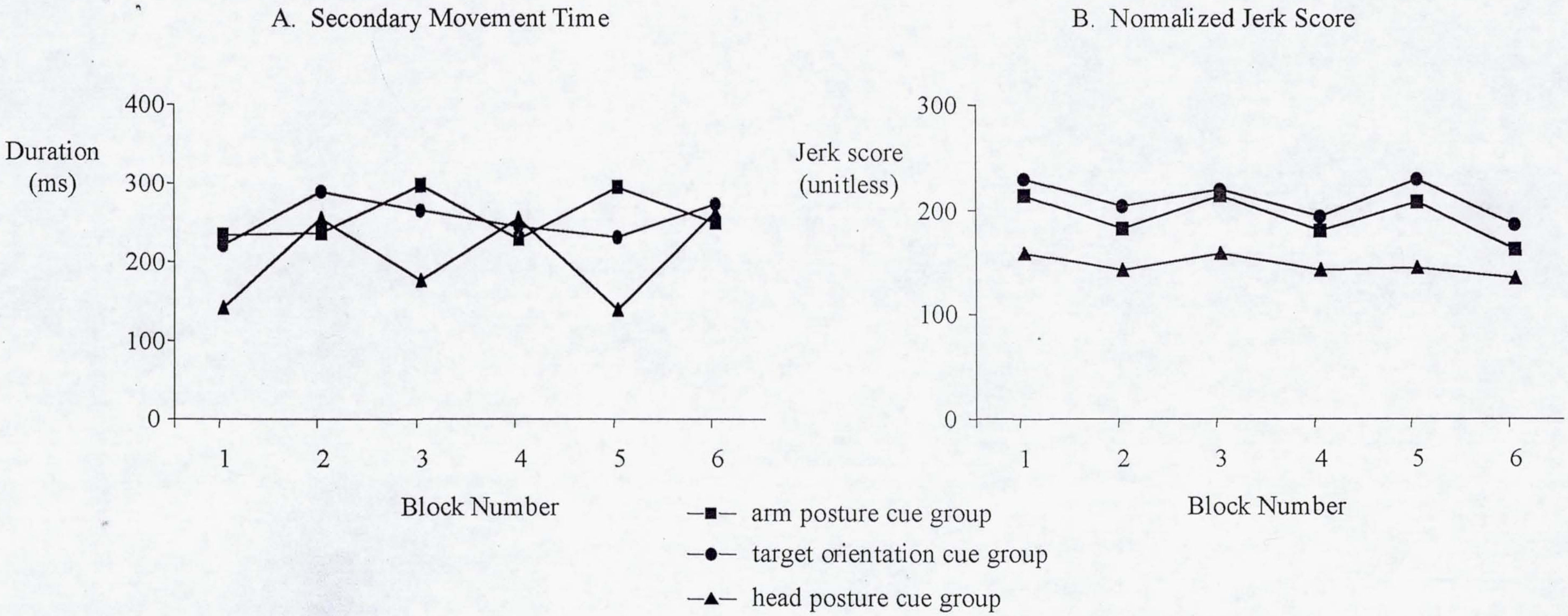

A. Secondary Movement Time
Duration (ms)
400
300
200
100
0
1
2
3
4
5
6
Block Number
B. Nomalized Jerk Score
Jerk score (unitless)
300
200
100
0
1
2
3
4
5
6
Block Number
—■— arm posture cue group
—●— target orientation cue group
—▲— head posture cue group

Fig.4

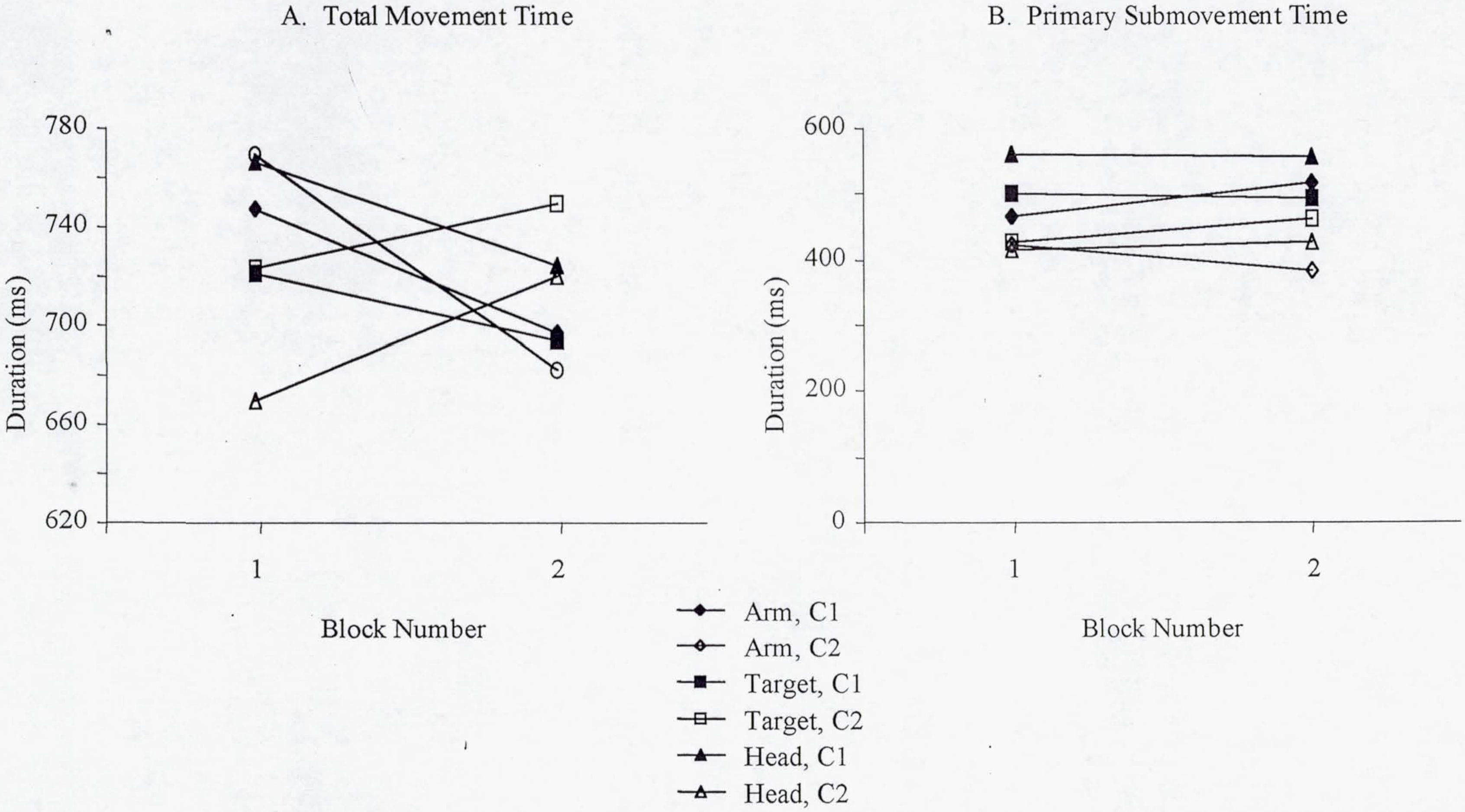
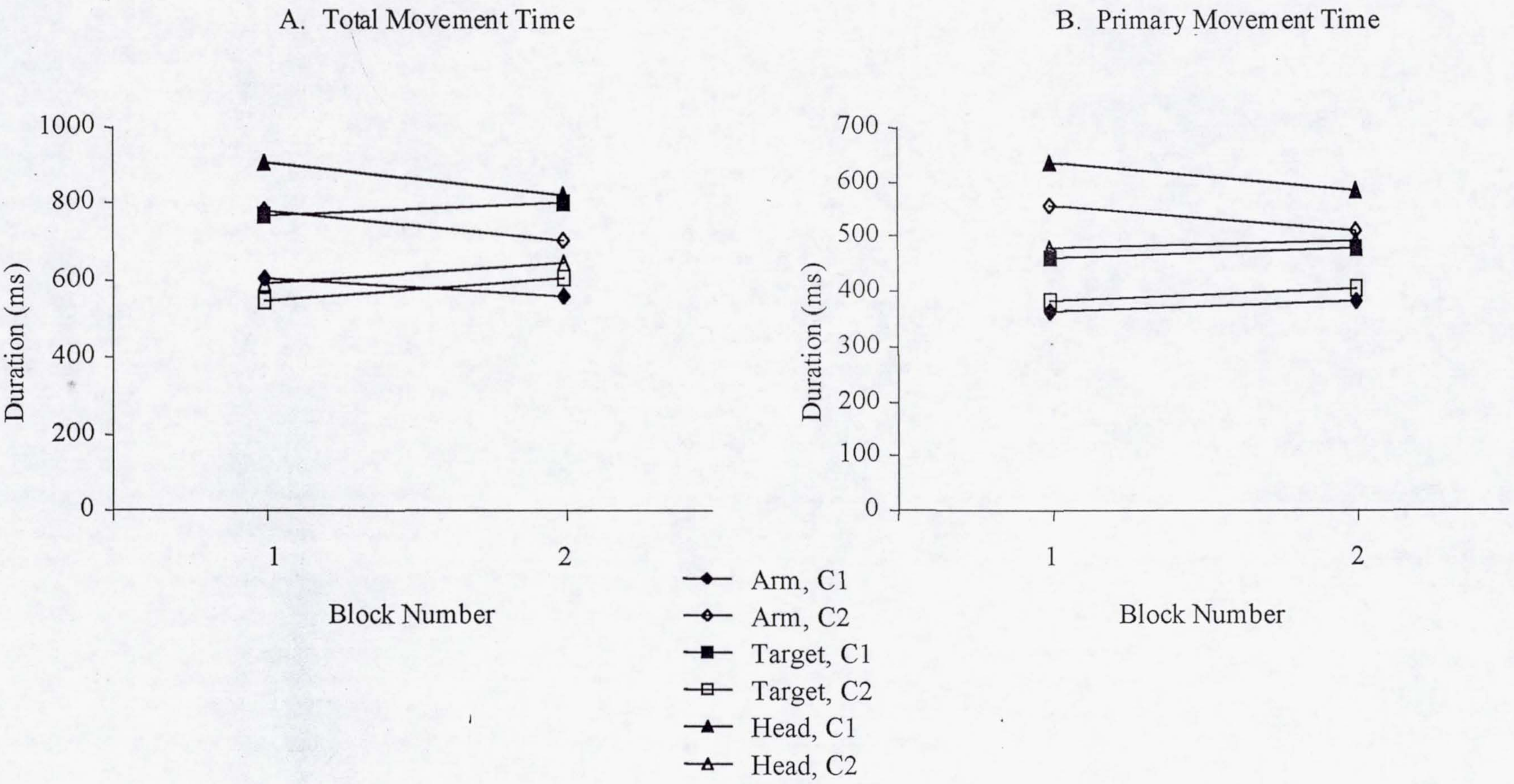

A. Total Movement Time
B. Primary Submovement Time
780
740
700
660
620
Duration (ms)
1
2
Block Number
600
400
200
0
Duration (ms)
1
2
Block Number
Arm, C1
Arm, C2
Target, C1
Target, C2
Head, C1
Head, C2

Figure 5


A. Total Movement Time
1000
800
600
400
200
0
Duration (ms)
1
2
Block Number
B. Primary Movement Time
700
600
500
400
300
200
100
0
Duration (ms)
1
2
Block Number
Arm, C1
Arm, C2
Target, C1
Target, C2
Head, C1
Head, C2