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# Where was my arm again? Memory-based matching of proprioceptive targets is enhanced by increased target presentation time

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ABSTRACT

Our sense of proprioception is vital for the successful performance of most activities of daily living, and memory-based joint position matching (JPM) tasks are often utilized to quantify such proprioceptive abilities. In the present study we sought to determine if matching a remembered proprioceptive target angle was influenced significantly by the length of time given to develop a neural representation of that position. Thirteen healthy adult subjects performed active matching of passively determined elbow joint angles (amplitude = 20° or 40° extension) in the absence of vision, with either a relatively "short" (3 s) or "long" (12 s) target presentation time. In the long condition, where subjects had a greater opportunity to develop an internal representation of the target elbow joint angle, matching movements had significantly smaller variable errors and were associated with smoother matching movement trajectories of a shorter overall duration. Taken together, these findings provide an important proprioceptive corollary for previous results obtained in studies of visually-guided reaching suggesting that increased exposure to target sensory stimuli can improve the accuracy of matching performance. Further, these results appear to be of particular importance with respect to the estimation of proprioceptive function in individuals with disability, who typically have increased noise in their proprioceptive systems.



Our sense of body position and movement independent of vision (i.e. proprioception) is critical for controlling motor activities. This has been highlighted in several investigations of individuals with compromised proprioception due to large fiber sensory neuropathy, who have known difficulties calibrating hand position in space [48], and dealing with multi-segmental limb dynamics [44,45]. Proprioceptive signals originate from multiple mechanoreceptors within the skin, joints and muscles, although there is now general agreement that muscle spindles provide the primary source of information regarding our proprioceptive sense [42]. This has been demonstrated frequently through muscle tendon vibration manipulations, which stimulate preferentially type 1a muscle spindle afferents and can produce illusions of joint position and motion consistent with lengthening of the vibrated muscle [4,5,11,25,43].

Beyond the above peripheral aspects of proprioception, there is also a significant central component to sensing bodily positions and movements in space. This aspect of proprioception was first brought to light in the early 1970s through studies assessing the accuracy of reaching to proprioceptive targets that were either established through active movement of the subject or passive displacement by the experimenter [27,35]. In these studies, subjects were most often found to be more accurate when matching actively-determined targets, presumably because they were able to incorporate knowledge regarding the target position from efferent movement signals. More recently, the influence of central proprioceptive processing factors has been extended to the cognitive domain. Indeed, using a common measure of proprioceptive sensibility (i.e., the joint position matching (JPM) task [7–10,13,17,18,14,22,47]), it has been shown that the ability of individuals to accurately match target joint positions is dependent on executive control factors such as memory and inter-hemispheric transfer of proprioceptive target information [17,22,23]. In this way, proprioceptive acuity assessment is not attributable simply to the quality of peripheral proprioceptive input signals relayed to the brain. Rather, proprioceptive task performance is influenced by

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how well such signals are processed to form central representations of target positions for the guidance of matching movements.

In an elegant series of studies involving the memory-based acquisition of visual targets, Lemay and Proteau [30,31] demonstrated that target presentation time is a key factor for accurately obtaining visual target locations. Specifically, subjects were asked to point to memorized targets that were flashed previously on a computer screen for either 50 or 500 ms. In the case where target durations were of a longer duration (i.e. 500 ms), subjects were not only more accurate in terms of variable error, but also showed changes in movement strategy, as reflected by their movement kinematics (i.e. peak velocity, movement time). These results were interpreted as being evidence for improved visual target perception with longer exposure time, likely facilitating incorporation of the target position into memory.

In the present study, we sought to determine whether a similar effect of target presentation time exists within the proprioceptive domain. This was accomplished by comparing subject performance on a memory-based JPM task with either a relatively short (3 s) versus long (12 s) target presentation time. In accordance with Lemay and Proteau [30,31], we predicted that longer target presentation times would allow for the development of enhanced representations of limb position and, subsequently, would improve memory-based matching. Additionally, we were interested to see if such improvements were accompanied by alterations in movement kinematics. Here, it was hypothesized that enhanced target representations with longer target presentation times would result in matching movements that required fewer movement corrections, as reflected by a shorter total movement time and smoother trajectory.

A convenience sample of 13 healthy adult participants (mean ± SD age = 20.44 ± 1.33 years; four males) with no evidence neuromuscular impairment were recruited from the University of Michigan student population. All participants were deemed to be right-handed, as evidenced by their laterality quotient (mean ± SD laterality quotient = +90 ± 10; range = +70 to +100) on the modified version of the Edinburgh Handedness Inventory [41]. Subjects also demonstrated right arm dexterity advantages (mean ± SD pegs right hand = 33.3 ± 4.8; mean ± SD pegs left hand = 30.5 ± 3.9) on a 60 s peg placement task (Purdue pegboard, Lafayette Instrument Co), as well as a right arm grip strength advantage (mean ± SD grip strength right hand = 37.6 ± 12.3; mean ± SD grip strength left hand = 36.9 ± 13.4) measured with a hand force dynamometer (Jamar®). Written, informed consent was obtained from each participant prior to testing. All procedures were approved by the local institutional review board of the University of Michigan and were in compliance with the ethical standards laid down in the 1964 declaration of Helsinki.

The experimental setup for this study has been described previously in detail elsewhere [17,21,22]. Briefly, blindfolded participants were seated with their forearms placed comfortably atop two height-adjusted, frictionless pivot manipulanda designed to measure angular displacement about the elbow in the horizontal plane. Standard starting positions of approximately 80° abduction and 15° flexion at the shoulder, 100° extension at the elbow, and neutral at the wrist, were maintained across participants. Prior to testing each subject was given several practice trials in order to acclimate them with the equipment.

The experimental procedure consisted of multiple memory-based elbow JPM trials performed in a pseudo-randomized fashion. Each JPM trial consisted of two phases: target establishment and target matching. During target establishment, the subject's right elbow was extended passively from is starting angle to a target position of 20° or 40°. Passive displacement was used to minimize any central effects related to the availability of an efferent motor signal for matching. In the "long" presentation time condition, the elbow was held at this target angle for 12 s. In the "short" condition, the target was held for only 3 s. Following the 3 or 12 s hold time, the elbow was passively brought back to the start position. The matching phase then began with the experimenter giving the subject a verbal, "match" command at a delay time of approximately 1 s. At this point, the participant reproduced actively the target elbow position with the same arm based on the memorized target angle. Despite known matching differences due to encoding specificity [28], active reproduction was preferred over passive matching in this study, as we were interested in the more functionally relevant task of planning and reaching to a target.

Five trials of data were obtained from each combination of amplitude and target presentation time condition. A random block design was utilized such that each subject performed blocks of trials with the same target presentation time (randomized order across subjects) and target amplitudes that were randomized within each block. Change in elbow joint displacement was recorded as the voltage output of precision potentiometers mounted beneath the pivot point of each manipulandum. The analog signal was digitized at 100 Hz, filtered (fourth-order Butterworth, zero phase lag, 8 Hz), and multiplied by a displacement calibration coefficient prior to data analysis.

Two measures of matching accuracy were used to characterize the effect of target presentation time on proprioceptive acuity. Constant error, defined as the signed difference between the final target and matching positions, was used to give an indication of average accuracy across trials, as well as any directional bias (i.e. positive values indicated overshooting of the target and negative values indicated undershooting). Secondly, variable error, defined as the standard deviation of the constant errors across the trials, was used as a measure of matching variability. For the sake of all analyses, target and matching joint amplitudes were determined by differentiating displacement (i.e. position) signals into velocity and then using a threshold-detection algorithm of ±2 SDs from the baseline (zero velocity) signal to detect movement onsets and offsets.

Three kinematic measures were also calculated in order to determine the effects of target presentation time on matching movement strategy. These measures included peak velocity, total movement time, and movement smoothness. Peak velocity was the maximum velocity achieved during the matching movement, whereas movement time was quantified as the difference in time between the matching movement offset and onset. Movement smoothness was assessed by a jerk (third derivative of the displacement) score value, which was normalized for both movement amplitude and duration [26,46]. This variable is a reflection of the number of discontinuities (i.e. corrections) in the reaching movement and is calculated according to the following formula:

$$\text{Jerk Score} = \text{sqrt}\left(\frac{1}{2}\int j^2(t)dt\,\frac{d^5}{a^2}\right)$$

where $j$ is the third derivative of position (i.e. jerk), $d$ is the movement duration, and $a$ is the movement amplitude.

Statistical analyses were conducted using a two presentation time (12 s versus 3 s) by two amplitude (20° versus 40°) multivariate analysis of variance (MANOVA). The MANOVA included all five dependent variables (i.e. variable error, constant error, peak velocity, movement time, and movement smoothness) and main effects (tested with an alpha threshold of $p > 0.05$) were decomposed by a simple comparison of means within the significant factor. No interactions were found for any of the dependent measures. The mean ± SD presentation times achieved by the experimenter across all subjects were 3.02 ± 0.63 s for the 3 s target presentation time condition and 11.42 ± 0.89 s in the 12 s target presentation time condition. One sample $t$-tests verified that these values were not