Adaptation to Delay while Playing Pong: Time or State Representation

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When we knock on the door, our sensory system receives inputs from different modalities: we see the hand touching the door, sense its haptic feedback, feel our arm stretched toward the door, and hear the knock sound. Although these sensory inputs propagate in different velocities to the relevant brain areas to process the information, we perceive them as being simultaneous, which raises the question of how the brain compensates for such time delays. One possible option to synchronize these signals is by using a mechanism that represents delays as time lags. Here, however, we suggest that time delays in the sensorimotor system can be represented by a mechanism that uses state variables, such as position and velocity, rather than actual time.

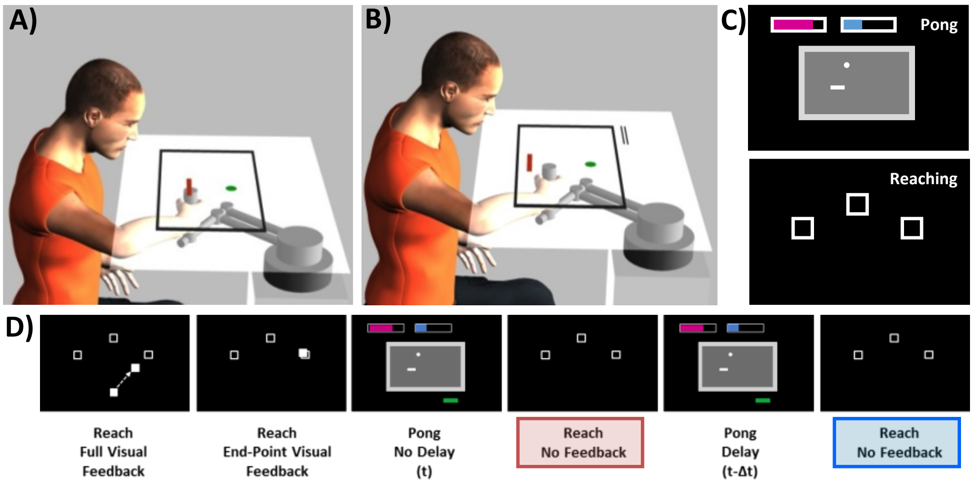
To test this hypothesis we used a virtual game of pong, in which participants were asked to hit a moving ball by controlling a paddle presented on the screen. The game had two sessions, one in which the position of the paddle was synchronized with the hand position (Figure 1A), and in the other, the paddle position was delayed by 100ms with respect to hand position (Figure 1B), i.e. $x_{paddle}(t) = x_{hand}(t-\tau)$, where τ represents the time delay. Before and after each pong session, participants performed reaching movements with no visual feedback of their hand location towards three targets located 12 cm from an initial position (Figure 1C and 1D). Results of the reaching movements showed that after adapting the delayed environment participants overshot targets (Figure 2A). While participants were able to reach close to the targets after playing the non-delayed session of the game (13.50±0.07, *mean amplitude* ± *std*), following the delayed session they increased their movement amplitude (15.17±0.11 *mean amplitude* ± *std*). The difference in reaching amplitude between the two sessions was found to be statistically significant (Figure 2B, $ANOVA_{RM}$ $F_{1,19}$=6.54, p=0.019).

To explain the behavioral results, we tested two alternative internal models that differ in the way time delay perturbation is represented. One model is based on a time representation, suggesting that we adapt to environment's time delay by updating the estimation ($\tilde{\tau}$) of the actual time lag, i.e. $x_{paddle}(t) = x_{hand}(t-\tilde{\tau})$. The second model suggests that time delay is approximated by combining the hand position and velocity using a mechanical system which consisted of a spring (K) and a damper (B), i.e. $x_{paddle}(t) = x_{hand}(t) + (B/K)\cdot \dot{x}_{hand}(t)$. This representation was based on the possibility of approximating a delayed variable as a Taylor series containing the non-delayed variable and its successive temporal derivatives.

We simulated the experiment protocol with a two-link arm model and tested its performance for each of the two internal models for representing the delayed feedback while playing pong. Simulation results showed that when using a time based internal model, reaching end point movements towards targets are quite accurate after the delayed pong session (Figure 3A), whereas a state based internal model generates target overshoot (Figure 3B). Overall, for the time based internal model, no significance difference in movement amplitude was observed between the reaching performed prior and after the delayed pong game ($ANOVA_{RM}$ $F_{1,19}$=1.331, p=0.26, Figure 3C). However, for the state based internal model, similar to the behavioral results, there is a significant increase in movement amplitude after adaptation to delay ($ANOVA_{RM}$ $F_{1,19}$=510.4, p<0.001, Figure 3D). These results suggest that the time delay is compensated using a state-based representation rather than a time-based representation.

We believe that the understanding of time and space representation in the brain during the performance of a motor task has important implications on developing novel rehabilitation techniques for motor impairments, specifically those related to disruption of space representation such as in hemispatial neglect syndrome.

Figure 1: Setup and Protocol. (A) Experimental setup includes a virtual reality environment with a 2DOF manipulandum, and involves the following modalities: vision, haptic, auditory, and proprioception. The participant's hand was positioned under an opaque screen to prevent visual feedback of the hand. By moving the manipulandum the participant controls a paddle (red rectangle) on the screen and was asked to hit a ball moving across the screen (green circle) as many times as possible. B) During the experiment we delayed the paddle movement with regards to hand's movement by 100 ms, meaning that the auditory, haptic and visual signals resulting from the hit with the ball are all delayed with respect to proprioception. C) Experiment consisted of two tasks: Pong (upper panel) and Reaching (bottom panel). During the first pong session, that lasted 10 minutes, the hand and paddle were synchronized. During the second pong session, participants played for 30 minutes in the delayed environment. During the reaching sessions a target appeared in one out of three locations in space, and the participant was asked to reach and stop at the target. D) Experiment protocol. The experiment started with a reaching block with full visual feedback of the hand location using a cursor on the screen. In the next block, The participant only received feedback about the endpoint position of the movement. The other reaching blocks in the experiment had no visual feedback at any point during the trial. We asked participants to imagine as if there is a cursor, and to stop when they perceived their hand as it is located under the target. In each of these reaching blocks participants performed 15 movements towards each target. Between the reaching blocks there were two blocks of the pong game task, where the second one of those was introduced with a delay.



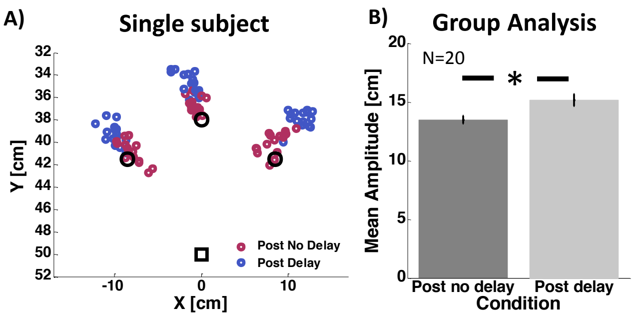


Figure 2: Experimental Results. (A) Single subject results during reaching. Movement started at the black square and targets are marked by black circles. Colored dots represent the end point location of the hand after finishing movements. The color code represents the reaching block; red for the block after the non-delayed pong and the blue for after the delayed pong. When reaching was performed after the non-delayed session of the pong, the movements ended around targets location. However, after 30 minutes of playing with delay, she overshot the targets. (B) Group analysis (N=20) show that the amplitude of the reaching movements after the delayed pong (light grey) was significantly larger than the amplitude after playing non-delayed pong (dark grey).

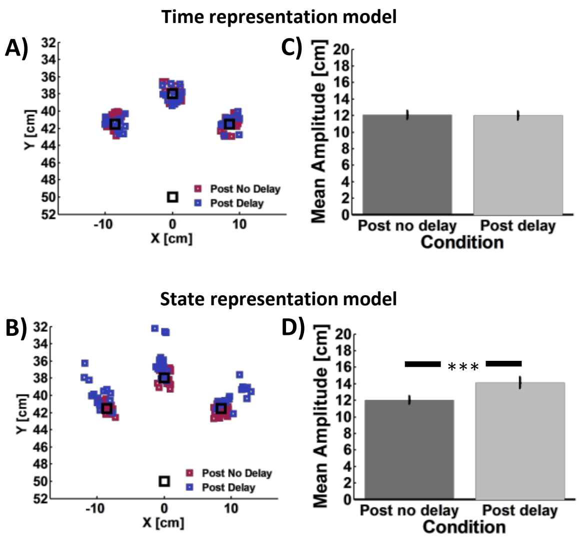


Figure 3: Model Results. Single simulation results during reaching using time-based internal model (A) or state-based representation (B). The color code is as in Figure 2. For both suggested models reaching movements after a non-delayed session of pong ended around targets location. However, only for the state-based model, reaching after the delayed pong session showed a tendency to overshoot the targets. Group analysis is based on randomizing various joint lengths and learning rates. According to a time representation based model (C), after the delayed pong session the performance during reaching did not change compared to reaching after the non-delayed session. However, while using the state representation based model (D), the simulated arm overshoot the target. The results for the state representation based model are consistent with the experimental results (Compare with Figure 2B).

References: [1] Pressman, A. **Simultaneity in the Human Motor System**, *PhD dissertation*, Department of Biomedical Engineering, Ben-Gurion University of the Negev, Israel (2012). [2] Avraham G, Mussa-Ivaldi FA and Karniel A. **Dealing with Delay while Playing Pong- Simultaneity and State Representation**, *Society for Neuroscience*, San Diego, CA, USA (2013).

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