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Non-target stimuli in the visual field influence movement preparation in upper-limb reaching

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Abstract

The present work provides an empirical test of the Dynamic Field Theory of visuospatial cognition. The Dynamic Field Theory is a bi-stable neural network model applied to explain how visual information is integrated during the preparation of reaching responses (Erlhagen and Schöner, 2002). The dynamic field theory posits that motor cortices develop peaks of activation for each possible target in the visual field. Targets that are close in space produce neural peaks with overlapping distributions, whereas targets that are far apart produce distinct peaks with non-overlapping distributions. As such, the Dynamic Field Theory predicts reaction times to potential targets that are close in space will be faster than those to targets that are far apart. The present work examined how proximal and distal distractors impact reaction time in an upper-limb reaching task. The results demonstrated that distal distractors result in prolonged reaction times compared to proximal distractors. We suggest that reaction time represents the time required to inhibit neural activity representing the location of the distractor. Thus, prolonged reaction times observed for distal distractors reflect the temporal demands associated with the competition of two non-overlapping distributions of activity in the brain. These findings support the tenets of the Dynamic Field Theory and demonstrate that non-target stimuli in the visual field can influence movement preparation.

Keywords

reaction time; movement preparation; dynamic field theory; reaching

Humans are continuously faced with multiple targets for action and must decide which potential action to perform at any given moment. In addition to deciding what to do or which object to interact with, humans must decide how to execute the most appropriate action by defining the temporal and spatial parameters of the movement. Animal studies demonstrate that neural activity in dorsal premotor cortex [1–3] and posterior parietal cortex [2, 4, 5] preceding movement reflects movement parameters to multiple potential targets of action. To this end, the motor system continually updates relevant sensory information, as well as

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information about the likelihood of interacting with each object. This idea is consistent with an ecological perspective [6] in which humans have evolved to interact with their environment in real-time, with a central nervous system that integrates available sensory information to specify the metrics (e.g., the trajectory of the hand) of multiple potential actions while simultaneously accumulating evidence to determine which action is most appropriate [1, 7–10].

On a neural level, multiple movement outcomes are represented by distributions of neural activity that are influenced by partial information about possible alternatives [7, 8, 11–13]. When potential movement outcomes are disparate from one another, the distribution of neural activity reflects discrete, mutually exclusive peaks of activation. In contrast, when movement outcomes are closer together, they form a larger, continuous plateau of activation [1, 7, 8]. The behavioral consequence is that movement preparation is shorter when the spatial disparity between potential movement outcomes is reduced relative to when they are farther apart [9, 14, 15]. Consistent with these animal studies, the Dynamic Field Theory of movement preparation [9] suggests that the time required for one neural distribution to reach threshold and the other to decay is directly influenced by the spatial location of competing actions. The present work provided an empirical test of the Dynamic Field Theory in an upper-limb reaching task in healthy young adults.

Participants were shown two potential targets in the visual field. Targets could appear in any two of five possible locations. Coincident with a tone, one of the two targets was visually identified as the action target, and participants pointed to that target as quickly and accurately as possible. We hypothesized that remote, but not proximal, distractors would elicit longer RTs because a degree of dimensional overlap exists when multiple potential targets are in close spatial proximity to one another [16]. In particular, the computational demands of response preparation would be reduced as a result of decreased uncertainty when two potential targets were adjacent to one another.

Methods

Seventeen participants (12 male; mean age = 21.18, ranging from 19–25 years) volunteered for the experiment. Participants were naïve to the hypothesis being tested and were all right-hand dominant as determined by the Edinburgh Handedness Inventory (Oldfield, 1971). All work conducted was reviewed by The Pennsylvania State University International Review Board and was in compliance with their ethical standards. All procedures were carried out with the understanding and written consent of each participant.

Participants were seated at a custom-designed virtual aiming apparatus, the Kinereach® virtual reality workstation (EZ Kinetics, State College, PA), which provides real-time 3-dimensional data acquisition for movements of the upper limbs. As shown in Figure 1A, the top shelf of the Kinereach® holds a 60" Vizio E Series Razor LED Television (refresh rate = 120 Hz), which projects to a one-way mirror that comprises the middle shelf. The distance between the television and the mirror is 24 cm. This geometry created the illusion that targets shown on the mirror are on the reaching surface, which comprised the bottom shelf of the Kinereach®. The one-way mirror occluded vision of the arms and thus visual

feedback about the location of the right index finger was provided by a cursor. Participants were secured in a Corbeau Racing chair (Corbeau USA, Sandy, UT) that had shoulder harness belts to prevent confounding torso motion. The chair's height and distance from the table was adjusted to achieve optimal position for completing the reaching tasks. The right arm was secured in a wrist splint to prevent wrist and finger movement. The splint was mounted to air sleds that eliminated the effects of friction and gravity.

The trakSTAR Magnetic Tracking System (Ascension Technology, Shelburne, VT) was used to collect six degrees of freedom across three movement planes at 116 Hz. A trakSTAR magnetic sensor was attached to the dorsal surface of the participant's right hand and a second sensor was attached to the right lateral deltoid. These sensors were then calibrated by a third sensor to determine the positions of the finger, wrist, elbow and shoulder joints in relation to the x, y, z coordinate system. Sensors were attached using Mueller MWRAP (Mueller Sports Medicine, Prairie du Sac, WI).

Stimuli included five targets and one start location. Each target had a diameter of 3.5 cm and was 5 cm along the x-axis from the next target. Targets were labeled according to region in the workspace: far left (FL), left (L), middle (M), right (R) and far right (FR). The start circle had a diameter of 2 cm, was in line with the middle target, and was located 17 cm posterior to the target array.

Each trial was initiated by the participant moving their finger to the central start position. Once in the start circle, two of the five possible targets appeared. As shown in Figure 2, after 400 ms, one of the two targets changed from gray to blue, one remained gray, and a tone signaled movement onset. Participants were instructed to point to the blue target as quickly and as accurately as possible in response to the tone. Targets and distractors were randomized into twenty different pairs, 10 with the right target as blue and 10 with the left target as blue, and were repeated eight times, for a total of 160 trials.

The trakSTAR Magnetic Tracking System records displacement of joints and limb segments with a maximum static and dynamic measurement error of approximately 2 mm³. Kinematic data were processed with custom software programmed in IgorPro (WaveMetrics, Inc., USA). The data were smoothed using an 8 Hz dual-pass Butterworth filter and differentiated to yield velocities and accelerations of limb joints and segments. Tangential hand velocities were used to identify movement onsets and terminations. Movement onset was defined by the last minimum before tangential velocity (tanv) that was less than 0.01 m/s. Likewise, movement termination was defined by the first minimum after peak tangential velocity (tanv) less than 0.01 m/s [17].

Reaction time (RT) was the time between the auditory cue and movement onset. Movement time (MT) was the time between movement onset and movement offset. RT and MT were submitted to 5 (target position: FL, L, M, R, FR) by 4 (distractor position: FL, L, M, R, FR) repeated measures analysis of variance (ANOVA). Note that due to the stimulus array, a 5 by 5 ANOVA is not possible. For example, in a given trial, the FL target could be accompanied by the L, M, R, and FR distractor. Main effects were decomposed by paired t-tests. Interactions for target by distractor were decomposed by examining the effect of the

distractor at each target location via univariate ANOVA and subsequent paired t-tests. These planned comparisons were an explicit test of the hypothesis and followed a significant omnibus F-test. Therefore, all tests were evaluated at $\alpha = .05$ and were not subjected to conservative corrective measures.

Results

The results for RT yielded an effect of target, $F(4, 64) = 4.84$, $p = .002$, distractor position, $F(3, 48) = 4.59$, $p = .007$, and an interaction for target by distractor position, $F(12, 192) = 8.24$, $p < .001$. The interaction is plotted in Figure 3A, which shows RT as a function of distractor position for each target. To decompose this interaction, we examined the main effect of distractor position at each target position. F-statistics for each univariate ANOVA are reported in Table 1. As noted with asterisks in Figure 3A, the position of a distractor influenced RT for every target position except the M target. The main effect of the distractor at the four target locations was subsequently examined by planned paired t-tests. The posthoc results are shown in Figure 3B – 3F and t-statistics are reported in Table 1. In general, RTs were shortest when a target was surrounded by an adjacent distractor and were longer when the distractor was in a more disparate location.

The results for MT elicited an effect of target, $F(4, 64) = 37.00$, $p < .001$, such that MTs were slowest to the FR target and decreased as a function of placement on the x-axis. Pairwise t-tests for target position revealed that MTs were different ($ps < .001$) for all pairs with the exception of M-FR targets ($p = .658$) and R-FR targets ($p = .076$).

Discussion

This study examined the influence of a non-target stimulus (i.e., a distractor) on RT when reaching to an adjacent or disparate target. The two-target task used in the present work is similar to that employed in animal studies investigating neural activity during movement preparation and execution [1, 7, 8]. The current work has two main findings. First, proximal, but not remote, distractors led to faster RTs. Second, the position of a distractor did not influence RTs when reaching movements were directed to a target coincident with body midline.

The finding that movement preparation is reduced when a distractor is adjacent to the target is consistent with predictions from our previous work examining visuomotor mental rotation [18–21]. In this center-out reaching paradigm, participants are instructed to point to a location that represents a specific angular disparity relative to the visual stimulus. For example, a visual stimulus may appear in the 12'o'clock position and the instruction may be to point to a location 90° clockwise from the stimulus. A correct visuomotor transformation places the reaching movement at the 3'o'clock position. In a series of studies, we demonstrated that movement planning was more efficient and effective when the angular disparity between the visual stimulus and reaching response is small compared to when it is large. This finding is consistent with the current results, as well as animal studies [1, 7, 8, 11] demonstrating that the motor system simultaneously encodes multiple action alternatives with distinct neural activation profiles. When a target is selected for action, neural activity

representing that alternative continues to build, while the neural activity representing other alternatives decays. The Dynamic Field Theory [9] suggests that the time required for one neural distribution to reach threshold and the other to decay is directly influenced by the spatial location of competing actions. The results of the present work directly support the Dynamic Field Theory of movement preparation.

The finding that RTs for movements directed to the midline target were not influenced by the position of a distractor is not surprising because body midline provides a physical anchor for the calculation of an internal egocentric frame of reference [22, 23] from which actions in peripersonal space can be organized [23, 24]. The perception of body midline is the sum of visual, vestibular, and proprioceptive information, all of which were held constant in the present work. Actions that fall along body midline may be preferentially encoded in the motor system and therefore not as strongly influenced by non-target stimuli. As shown in Figure 3D, in spite of the fact that the results did not bear out an effect of distractor for this target, the trend is in line with the results for the other targets. This suggests that the same neural processes for action competition were engaged during response preparation, but that the preferential encoding that may accompany targets coincident with body midline may supersede the influence of non-target stimuli.

The present work has implications for theories of action organization. We provide indirect evidence that neural activity simultaneously encodes a distribution of movement endpoints. This is consistent with ecological view of behavior: humans interact with a complex and dynamic environment with numerous alternatives for action. Information processing theories posit that actions proceed in a hierarchical manner in a series of distinct events, however, it is difficult to reconcile this idea with the continuous modification required for real-time interaction with the world. Indeed, numerous animal studies demonstrate that neural activity is continuous and not organized into serial phases [1, 2, 7, 8, 11, 25] and that the brain represents multiple alternatives in parallel [1, 26, 27].

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Highlights

- Reaction time (RT) reflects movement preparation processes.
- Non-target distractors in the visual field influenced RT in upper-limb reaching.
- Proximal distractors elicited faster RTs compared to distal distractors.
- RT may reflect time required to inhibit neural activity representing the distractor.

Figure 1.

The top shelf of the Kinereach® held a 60" Vizio E Series Razor LED Television that projected to a one-way mirror on the middle shelf. The geometry created the illusion that targets shown on the mirror were on the reaching surface, which comprised the bottom shelf of the Kinereach®. The right arm was secured in a wrist splint that was mounted to air sleds which eliminated the effects of friction and gravity.

Figure 2.

The experimental timeline and visual display. Participants were shown one target and one distractor. After 400 ms in the start position, an auditory tone sounded and the target turned blue. Participants were instructed to reach towards the blue target.

Figure 3.

(A) Reaction time (ms) as a function of each target and distractor position. Asterisks denote a significant main effect of distractor position for that target. Error bars represent standard error of the mean. (B-F) Reaction time (ms) as a function of distractor position for each target location. Asterisks denote significant differences in pairwise comparisons. Error bars represent standard error of the mean. (B) Reaction time (ms) for each distractor at the FL target. (C) Reaction time (ms) for each distractor at the L target. (D) Reaction time (ms) for each distractor at the M target. (E) Reaction time (ms) for each distractor at the R target. (F) Reaction time (ms) for each distractor at the FR target.

Table 1

The results of posthoc tests for the target by distractor position interaction for RT.

FL Target	F(3, 48) = 13.27, p < .001*
L vs. M distractor	t(16) = -1.38, p = .187
L vs. R distractor	t(16) = -3.58, p = .002*
L vs. FR distractor	t(16) = -5.47, p < .001*
M vs. R distractor	t(16) = -3.00, p = .009*
M vs. FR distractor	t(16) = -4.21, p < .001*
R vs. FR distractor	t(16) = -2.13, p = .049*
L Target	F(3, 48) = 9.42, p < .001*
FL vs. M distractor	t(16) = 0.16, p = .158
FL vs. R distractor	t(16) = -3.24, p = .005*
FL vs. FR distractor	t(16) = -4.88, p < .001*
M vs. R distractor	t(16) = -2.68, p = .016*
M vs. FR distractor	t(16) = -3.92, p = .001*
R vs. FR distractor	t(16) = -0.76, p = .460
M Target	F(3, 48) = 2.42, p = .078
R Target	F(3, 48) = 5.81, p = .002*
FL vs. L distractor	t(16) = 2.90, p = .010*
FL vs. M distractor	t(16) = 3.09, p = .007*
FL vs. FR distractor	t(16) = 3.67, p = .002*
L vs. M distractor	t(16) = -0.04, p = .966
L vs. FR distractor	t(16) = 0.72, p = .482
M vs. FR distractor	t(16) = 1.15, p = .267
FR Target	F(3, 48) = 4.62, p = .006*
FL vs. L distractor	t(16) = 0.24, p = .818
FL vs. M distractor	t(16) = 1.42, p = .174
FL vs. R distractor	t(16) = 3.91, p = .001*
L vs. M distractor	t(16) = 1.28, p = .220
L vs. R distractor	t(16) = 2.56, p = .021*
M vs. R distractor	t(16) = 1.68, p = .112

Significant tests are noted with an asterisk. All tests were evaluated at $\alpha = .05$.