Interaction of multiple future movement plans in sequential reaching

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Abstract

Real world actions often comprise a series of movements that cannot be entirely planned before initiation. When these actions are executed rapidly, planning of future movements needs to occur simultaneously with ongoing execution. However, it remains unknown how the human brain solves this task and whether planning processes of subsequent movements interact. Here we introduce a new sequential reaching paradigm in humans (N=10, 7 sessions each) with a horizon manipulation that allows us to study this interaction by controlling the timing and the overlap of the planning processes for individual movements embedded in the sequence. We show that at least two future reaches are planned simultaneously with the ongoing reach. Two results indicate that these planning processes are not independent of one another. First, correcting an ongoing reach is slower when future movements are planned. Second, the curvature of the current reach is modified based on the next reach only when the planning processes of the two reaches overlap sufficiently. The interactions between future planning processes may enable smooth production of sequential actions.

Introduction

Many everyday actions like saying a sentence or preparing a cup of tea are composed of a long and often rapid sequence of movements (Lashley, 1951). For successful performance of such tasks, the next movement needs to be proactively planned before the previous movement is concluded. Indeed, investigations in saccadic eye movement (McPeek et al., 2000; McPeek and Keller, 2002), reading (Rayner, 1998), walking (Patla and Vickers, 2003), typing (Snyder and Logan, 2014), finger movements (Ariani et al., 2021, 2020), path tracking (Bashford *et al.*, 2022), and reaching (Safstrom et al., 2014; Zimnik and Churchland, 2021) consistently show that movement production is faster and more efficient when participants have access to information for planning the future movements. This improvement demonstrates the nervous system's ability to plan future movements while executing the current movement – i.e., to do *online planning* (Ariani et al., 2021, 2020; Ariani and Diedrichsen, 2019).

Planning and execution related processes of a single movement occur in overlapping brain areas and often even in the same neurons (Crammond and Kalaska, 2000; Elsayed et al., 2016; Kaufman et al., 2014), so an important question is how the nervous system avoids interference between the planning of a future movement and the control of the current one in rapid sequential movements. In a sequence of two reaches, Zimnik and Churchland (2021) showed that, in primary motor cortex (M1) and dorsal premotor cortex (PMd), preparation of the next movement occurs in an orthogonal neural subspace to that which controls the ongoing movement, thereby allowing these two processes to run in parallel without interference. For longer and more complex movement sequences it may be necessary to prepare beyond the next movement. Indeed, for rapid sequences of finger presses, we have previously shown that human participants plan ~3 movements ahead of the current action (Ariani et al. 2021). It remains unknown whether the planning process of these multiple future movements interact with each other and with ongoing action, and how this is implemented in the brain.

Here we address whether and how multiple future movements interact in the context of a sequential reaching paradigm. The use of reaching movements offers multiple advantages over finger movements: planning processes for reaching movements can be probed easily using target displacements, co-articulation between different movement elements can be more readily observed, and additionally, the use of a reaching movement will make the discovered processes more accessible to neurophysiological investigation in non-human primates. Therefore, we developed a continuous reaching task, in which we control how many future movements can be simultaneously planned, and how much these planning processes can temporally overlap. We show that humans can plan at least two future reaches simultaneous with execution and that the planning of these two future movements depend on one another.

Results

We investigated how multiple future targets of a sequence are planned in a continuous reaching task. Participants were instructed to perform sequences of 14 reaches in a planar robotic exoskeleton. The targets were generated from a hexagonal grid of potential targets with radii of 1 cm spaced 4 cm apart over a 21x24 cm total workspace (**Figure 1A**). Every trial started from the same “home” target in the center of the workspace. Participants needed to capture a target before moving on the next target, which they did by staying within it for 75, 200, or 400 ms (**dwell time, Figure 1B**). Longer dwell times required a full stop in each target, while shorter dwell times allowed participants to link subsequent reaches into a coarticulated unit (**Figure 1C**).

Participants could see the position of their hand displayed as a circular cursor in the horizontal plane of the task. Participants were shown either one (Horizon 1), two (H2), three (H3), four (H4), or five (H5) future targets to control how much information about the future sequence was available. The order of future targets was indicated by their brightness. The Horizon 1 condition was equivalent to a serial reaction time task because the next target appeared only when the current one was captured. Therefore, the next movement could not be planned until the end of the current movement (**Figure 1D-H1**). In contrast, the Horizon 2 condition allowed for some planning of the next movement while executing the current one (**Figure 1D-H2**). Horizon 3-5 conditions allowed planning the next two, three or four movements, respectively (**Figure 1D-H3**).

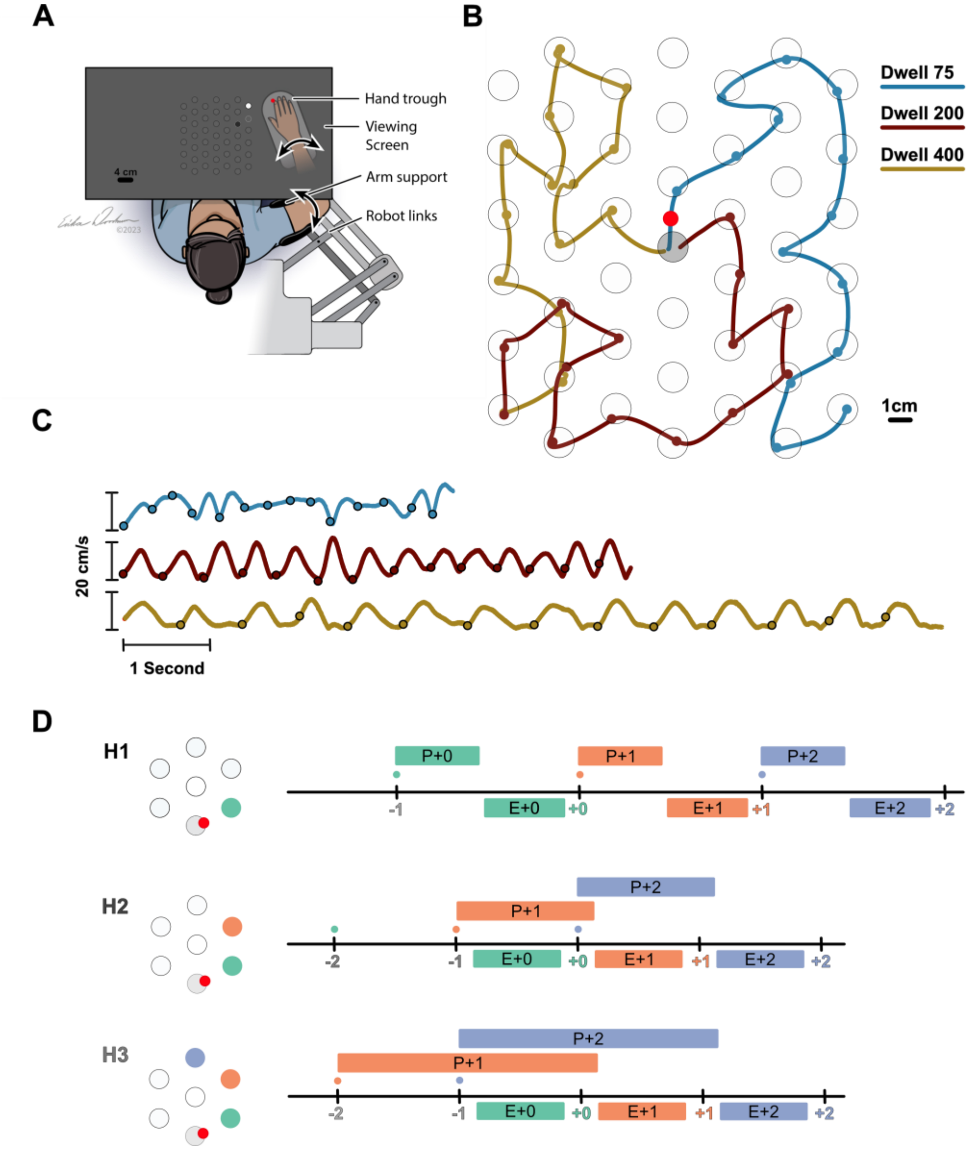

***Figure 1: Experimental Paradigm**. **A)** Participants performed reaches in an exoskeleton robot. Their hand was occluded, and hand position was indicated by a red dot. The targets and their order were shown with decreasing brightness (an H3 trial is shown). **B)** Movement trajectory in 3 example trials (Horizon 2; Dwell 75, 200, 400). Trials always started from a fixed home target in center (gray target). The small circles on the traces show the time point in which the target was captured. **C)** Speed profiles for the example trials shown in B. **D)** Timeline of the task for Horizon 1-3 conditions. Ticks show the time when the target was captured (colored number) and a new target was shown on the screen (colored small dot). The boxes above the line show the available time for planning each movement, and the boxes below the line show the execution for each planned movement.*

Movement speed suggests participants plan only one future reach

To establish how many future movements participants planned, we first asked whether they were faster when extra future targets were visible. To quantify participants' speed, we measured inter-reach interval (IRI), defined as the time required to move the hand from the boundary of one target to the boundary of the next (**Figure 2**). IRI was significantly reduced from Horizon 1 to Horizon 2 for all dwell times. The average reduction of IRI was 206 ms ($t_{(9)} = 20.7$, $p = 6.63e{-8}$), 232 ms ($t_{(9)} = 24.86$, $p = 1.32e{-8}$), and 246 ms ($t_{(9)} = 2.55$, $p = 2.82e{-8}$) for the 75, 200, and 400 ms dwell times, respectively.

We observed no further improvement when more targets were presented (H3-H5). There was a small 16 ms improvement from H2 to H3 in the 75 ms dwell time condition, but this effect remained non-significant ($t_{(9)} = 2.69$, $p = 0.12$). These results suggest that participants only planned one future target and that any further targets were being ignored. These results contrast with our earlier results for sequences of finger movements, where we found evidence of speed improvements up to Horizon 3 condition (Ariani et al., 2021).

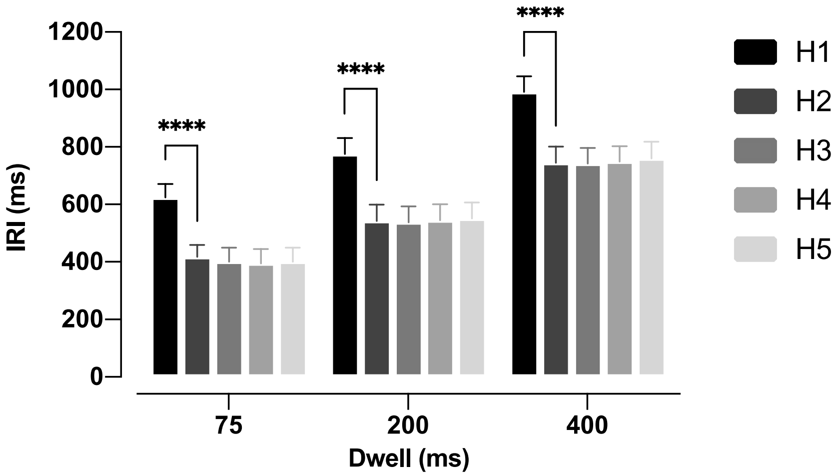

Figure 2: Inter-reach interval (IRI) for three Dwell Times and five Horizons. *IRI was averaged across all trials, all session, for each participant. The Error bars show a 95% confidence interval, and **** signifies p < 0.0001.*

Target displacements shows participants at least partially plan two future reaches

Finger movements and reaches differ in terms of the initiation of subsequent movements. With sequential finger pressing, the next movement can start before the current one ends because of the separated effectors. On the other hand, in sequential reaching, future reaches cannot be initiated even if they are fully planned. Thus, it remains possible that participants planned multiple movements ahead, without this manifesting in their overall speed. To probe directly whether participants used information about the target two reaches in the future (i.e., the +2 target), we occasionally displaced the +2 target when the +0 target was captured. If information about +2 target was not being used, we would see no interruption in the sequence: both the movement towards the unperturbed +1 target, as well as to the jumped +2 target should not differ from unperturbed conditions (**Figure 3B, thin line**). We tested this prediction in the H3 condition with 75 ms dwell time.

Our results indicate that information about the +2 target was being used. We observed a normal reach towards the unperturbed +1 target. The reach time to the +1 target was not reliably different between the jump and no-jump conditions ($t_{(9)} = 0.63$, $p = 0.54$; **Figure 3C, +1 Movement**). This was also true for dwell time inside the +1 target ($t_{(9)} = 1.98$, $p = 0.08$; **Figure 3C, +1 Dwell**). However, movement time from the +1 to the +2 target was significantly longer in jump condition ($t_{(9)}=5.90$, $p = 2.00e-4$; **Figure 3C, +2 Movement**).

One reason for this delay could be that visual displacement of the target was a distracting stimulus. However, kinematic analysis reveals that the movement towards the +2 target was at least partially planned. Specifically, participants reached to the pre-jump +2 target, and then, corrected their reach toward the new position of +2 target (**Figure 3B, thick line**). We quantified this commitment to the pre-jump +2 target position by measuring the minimum distance between the reach trajectory and the center of the pre-jump +2 target (see Methods). The minimum distance was significantly lower in the jump condition ($t_{(9)}$=5.78, p = 3.00e-4).

These results suggest that, despite not influencing the IRI, the reach to the +2 target was at least partially planned before the target jump, simultaneous with the reach to the +0 target and planning of the reach to the +1 target.

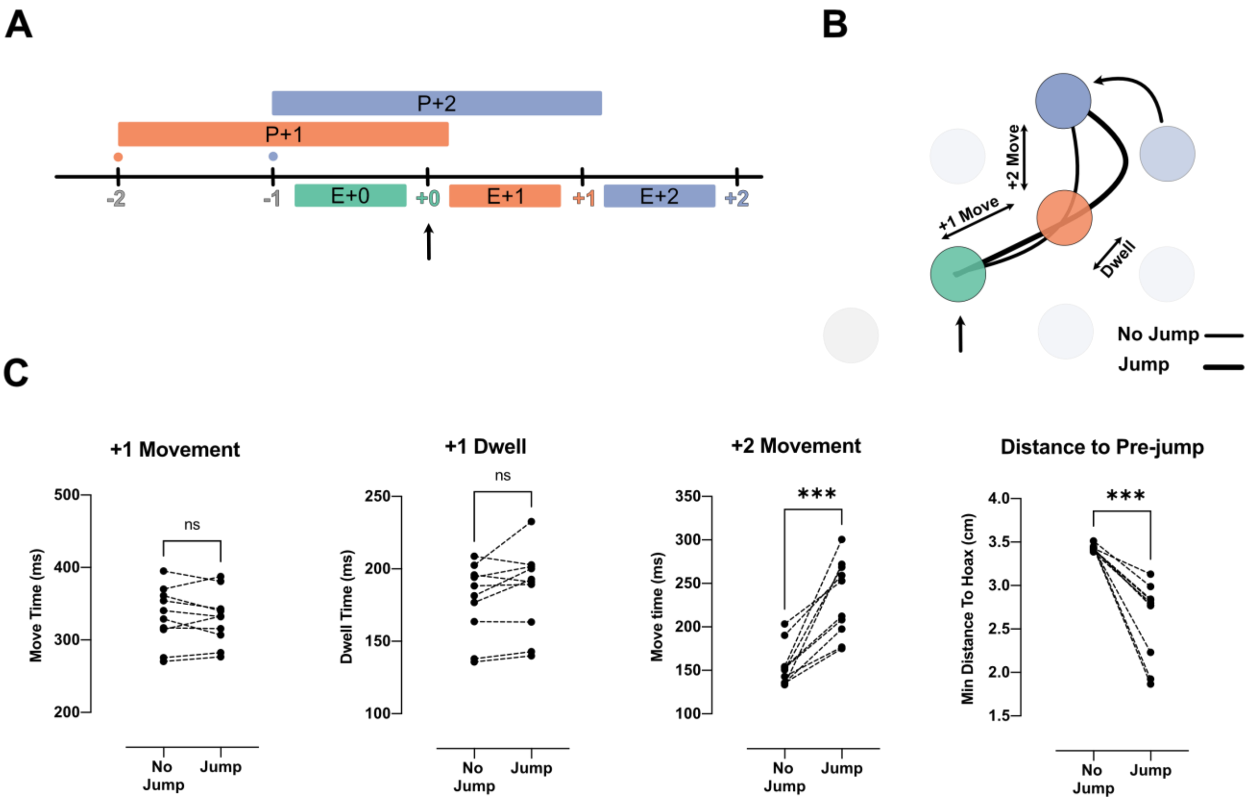

Figure 3: Jump of the +2 target reveals existence of planning processes for the reach toward +2 target during the execution of +0 reach. A) *Timeline of the jump experiment in Horizon 3, Dwell Time 75 ms condition. The jump occurred at the capture of +0 target (vertical arrow).* ***B)*** *Reach trajectory for an example no-jump trial (thin line) in which the pre-jump target (light purple) was not shown, and a +2 jump sample trial (thick line) in which the pre-jump target moved to a new position (dark purple) at the time the +0 target was captured (arrow).* ***C)*** *The time for +1 movement, +1 dwell, and +2 movement, and the minimum distance of reach trajectory to the center of pre-jump target for no-jump and jump and condition. Each dot represents one participant, *** shows p-value < 0.001.*

Planning processes for multiple future movements are interdependent

If multiple future movements are planned at the same time, are these preparatory processes independent of each other or do they interfere or interact with each other? Such interactions could arise simply because the two movements are planned together as a unit. Alternatively, planning the two plannings may compete for the same neural or computational resources.

We tested whether the two movement plans were interdependent by jumping the position of the +1 target when the +0 target was captured. This was done under the 75 ms dwell time. We compared the speed of the correction in the H2 and H3 conditions **(see Figure 4A and Methods**). Although the two conditions had similar kinematics, participants could only plan the +1 target in the H2 condition, whereas they could plan both the +1 and +2 targets in the H3 condition (**Figure 4A**). If the +1 and +2 targets are planned independently, the movement correction to a displacement of the +1 target should be the same in the H2 and H3 conditions. Alternatively, if the movements are planned together or share limited resources, the correction should be slower in the H3 condition because some of the resources would be assigned to planning the +2 target.

Consistent with the interdependent planning hypothesis, we found that the corrections for a +1 target jump were longer and slower in the H3 condition than in the H2 condition (**Figure 4B**). In both conditions, participants failed to correct the movement before arriving at the pre-jump position of the +1 target (**Figure 4B**). In the H3 condition, both the movement time ($t_{(9)} = 4.85$, $p = 1.80e-3$), and trajectory length ($t_{(9)} = 6.19$, $p = 3.00e-4$) of the corrective movement were longer than that of the H2 condition. The longer correction trajectory was due to participants moving onwards to the +2 target without having corrected for the displaced +1 target. We again used the minimum distance between the corrective reach trajectory and the +2 target to quantify this effect (**Figure 4C**). The corrective reaches were closer to the center of the +2 target in H3 condition ($t_{(9)} = 4.28$, $p = 4.00e-3$).

In summary, it took more time to update the +1 movement plan when participants could simultaneously plan both the +1 and +2 target as compared to when they could only plan the +1 target. This effect could indicate that planning a reach to the +2 target occupies some part of a shared computational resource such that less of the resource was available for updating the +1 target. Alternatively, the two movements may be planned together, and more time is required to update a two-step movement plan. Either way, these results indicate a clear dependence between the planning processes for future movements.

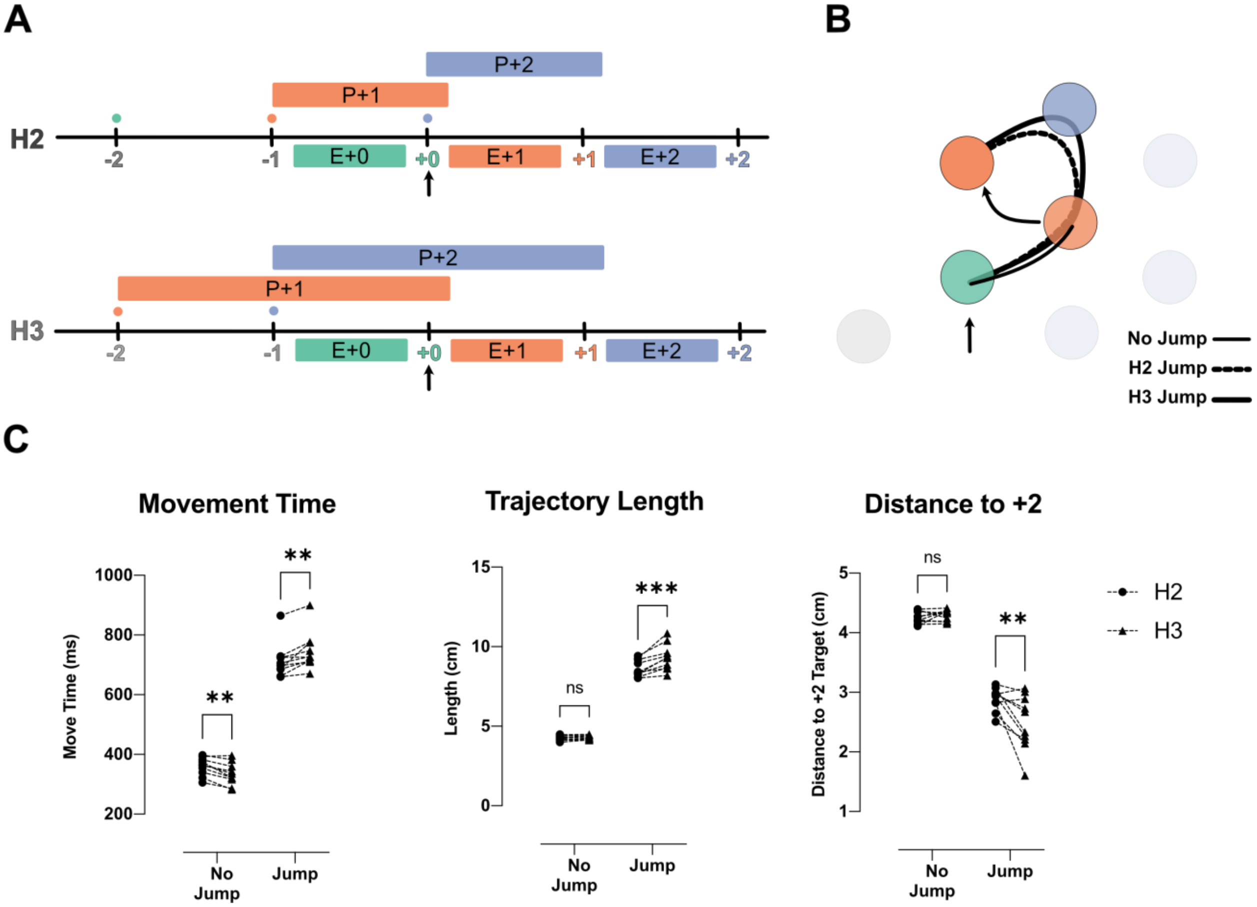

*Figure 4: **Correction for jump of the +1 target is delayed when more future movements are planned. A)** Timeline of the jump experiment in the H2 and H3 conditions. In both conditions, the jump of the +1 target (orange) occurred when the +0 target was captured (vertical arrow). **B)** Example trials for a no jump condition (thin line) and for jump conditions for H2 (thick dotted line) and H3 (thick solid line). In the latter two conditions, the +1 target (orange circle) jumped to a new position (curved arrow), when the +0 target was captured (vertical arrow). **C)** Movement time, Trajectory length, and minimum distance of the trajectory to the center of +2 target for the reach to the new position of the +1 target. Dots and triangles show mean values for each subject in H2 and H3 conditions respectively. ** and *** signify p-value < 0.01 and p-value < 0.001.*

Interaction of planning processes leads to biomechanically advantageous movements

The jump experiments above indicate that reach planning to the +1 and +2 targets interact with each other. Such interactions could allow the motor system to optimize the set of movements (Ramkumar *et al.*, 2016), leading to systematic co-articulation of the movement segments. That is, with enough planning time, each movement in the sequence could be optimized for the movement that comes after it.

Indeed, we observed systematic co-articulation of movements in the H3 condition (**Figure 5A**). When the +2 target demanded an upcoming rightward turn, the +1 reach curved left, and vice versa (**Figure 5B**). Although this deviation led to a longer overall trajectory, it reduced the required turning angle at the +1 target. To summarize the effect of future target on curvature, we fit a linear model that predicted the signed curvature value of the current reach based on the turning angle towards the +2 target (see **Figure 5C** and Methods). The model was fit for each dwell time and Horizon separately. This model has the advantage over simple averaging because it accounts for curvature changes caused by the previous movement. Figure 5C shows the average curvature for all possible +1 target angles, corrected for the influence of the last target. To summarize the co-articulation effect across all the angles, we fit a line between 5 values of angles and the curvature (**Figure 5B, black line**). The slope of the line summarizes the strength of the curvature effect (**Figure 5D**) for each dwell time and Horizon condition.

In the H1 and H2 conditions, the slope was not reliably different from zero, indicating no systematic co-articulation. This observation is expected since even in the H2 condition, the +2 target appeared right before initiation of the movement, not leaving enough time to influence the +1 movement. In the H3 condition, the slope was reliably smaller than zero for all the dwell time conditions, indicating systematic co-articulation once parallel planning was feasible. In the case of the 75 ms dwell time, the co-articulation kept growing from H3 to H4 ($t_{(9)} = 4.88$, $p = 3.00e\text{-}03$). We observed no reliable increase in co-articulation for Horizon >3 for the 200 ms ($t_{(9)} = 0.19$, $p = 0.98$) or 400 ms dwell times ($t_{(9)} = 0.24$, $p = 0.81$).

Overall, we observed less co-articulation for longer dwell times. Dwell time can have a dual role here. On the one hand, longer dwell times mean the participants have more time to benefit from future targets, because they see the targets longer, potentially leading to more co-articulation. On the other hand, longer dwell times means the participants had to stay stationary in the target for longer, making the movements less mechanically integrated, and therefore decreasing the benefit of co-articulation. To distinguish between these potential contributions of dwell time, we plotted the curvature effect versus the time that participants could see both the +1 and +2 targets before starting the +1 movement (**Figure 5E**). Both Horizon and dwell time led to more overlap in planning times. For all dwell time conditions, the curvature effect increased between H2 and H3, and then saturated after H4. However, with longer dwell times, the overall rise and saturation of the curvature effect was smaller ($F_{(2,18)} = 17.38$, $p = 6.26e\text{-}05$), suggesting less interaction between planning processes when the movements are biomechanically separated.

Together, these results show that, with enough time, the planning processes of future reaches interact with each other to produce biomechanically advantageous movements.

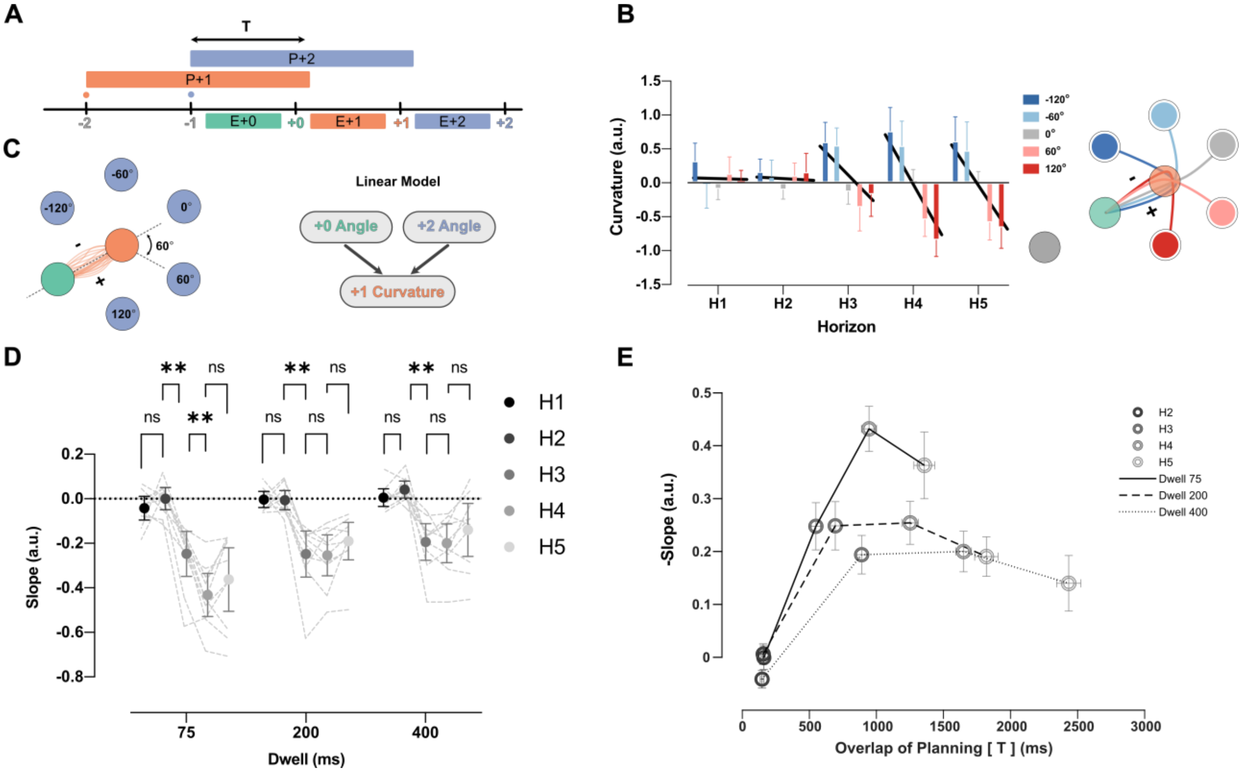

Figure 5: Curvature of the reach to +1 target is modulated by position of +2 target. A) *Timeline of planning and execution for a Horizon 3 trial. The black arrow shows the time that planning processes for reach to +1 and +2 target overlap.* ***B)*** *Effect of +2 target angle on the curvature of +1 reach for Dwell time 75, all Horizons, one participant. Positive value of curvature indicates downward curve and vice versa. The overall effect is captured by the slope of the line relating average curvature to the five angles (slope of black lines).* ***C)*** *All the reaches are aligned to one start point and one direction. Then, the angle at the start of the movement to the +2 target can be -120, -60, 0, 60, 120 degrees (60 is shown with dotted line). A linear model is used to predict the signed curvature based on the position of last target (+0 angle) and the +2 target (+2 angle).* ***D)*** *Each dot represents the average summary statistics of the curvature across participants. Individual participant values are shown with shadowed dotted lines in the background.* ***E)*** *Average curvature effect across participants vs overlaps of planning time (T) for each condition. Shades of gray show different Horizons and solid, dashed, and dotted lines represent different Dwell Time conditions. Error bars are SEM, and ** signifies p-value < 0.001.*

Discussion

Planning horizon in sequential reaching vs finger presses

In a previous finger sequence study, using a similar horizon manipulation to the one used here, we found that participants executed sequences faster when they had information about multiple future finger presses. This benefit increased up to horizon of 3 future finger presses (H3) and then plateaued (Ariani *et al.*, 2021). Consistent with these findings, we observed a large reduction in movement time when participants were provided with one future reach target (**Figure 2, H1 to H2**). However, the benefit of having a second future target was only evident in the shortest dwell time **(Figure 2, dwell 75; Figure 4C)**, but not in the longer dwell times **(Figure 2, Dwell 200, Dwell 400)**. In these longer dwell times, we failed to find faster performance for more advanced knowledge likely because the participants had sufficient time to complete the planning during the dwell period. It is also possible that this difference arises because the transformation of the visual cue to motor plans is faster for the direct target-to-reach mapping used here than for the more abstract number-to-finger mapping used in our previous study (Diedrichsen et al., 2001; Goodman and Scott Kelso, 1980).

Even though the planning of multiple future movements could not be seen in terms of movement time, our experiments with target displacements provide clear evidence that participants had planned two movements ahead (**Figure 3**). Overall, these observations suggest that the availability of the second reach target can be more significant when faster execution of the task demands faster transformation of visual cue to muscle commands, or when the cue-to-action mapping is more demanding.

Interdependence vs. independence of future movement plans

If participants plan multiple future movements at the same time, the next question is whether these preparatory processes run independently or if they interact with each other. We investigated these possibilities by jumping the target that participants were about to reach towards. The participants corrected the reach only after initially reaching toward the pre-jump position of the target (**Figure 4B**). This behavior is similar to the work by Ames et al. (2019) where target displacement during execution led to an initial commitment to the pre-jump position of the target, followed by a smooth corrective reach toward the new target position. Neurally, the authors showed that resource distribution in M1 and PMd is accomplished by re-planning the corrective reach in a subspace orthogonal to the one controlling the ongoing movement (Ames et al., 2019). In our study, we asked whether the re-planning process depended on any other planned future movement **(Figure 4)**. Interestingly, the corrections were slower when more future targets were known to the participants (**Figure 4B**), indicating some interaction between the two future planned reaches. This interdependence could come in multiple forms. One possibility is that the neural resources dedicated to re-planning have to be split between preparation of future targets, slowing the replanning of the next movement (Kornysheva *et al.*, 2019). Alternatively, the two future movements may be prepared as a chunk (Ramkumar *et al.*, 2016), and changing the entire chunk may take longer time than changing a single movement. Either way, probing the planned state with target perturbations, the results clearly demonstrate an obligatory interaction between multiple future movement plans.

We also provide evidence that the interactions between future movement plans can improve performance. When the planning processes of two future reaches overlapped sufficiently, we found changes in the curvature of the current reach that anticipated the direction of the next reach target. The curvature was opposite to the direction of the next target, making this co-articulation advantageous from a biomechanical point of view (**Figure 5D**). The observed curvature interaction can be either due to fully chunked planning of two elements, or alternatively, due to separate, yet interactive, planning of the two reaches. The former possibility seems less likely since the interaction was observed even when movement segments were fully separated by a long dwell time (**Figure 5D, Dwell 400**).

Implications for the neural control of online planning

What implications do our results have for the neural processes underlying online planning of multiple future actions? Previous neurophysiological investigations showed that individual neurons can be involved in both the planning and execution of phases of a movement (Churchland and Shenoy, 2007; Crammond and Kalaska, 2000; Elsayed et al., 2016; Kaufman et al., 2014). Nonetheless, when two movements are concatenated, the planning of the second movement can be proceed in parallel with the control of the first movement. This lack of interference can be explained by the fact that planning and execution proceed in orthogonal neural state-spaces (Zimnik and Churchland, 2021).

The phenomena demonstrated in this behavioral study raise the question of how the planning processes for multiple future movements are realized in the brain. One hypothesis is that the two future movements are also planned in orthogonal neural state space without any interactions during the planning phase. Under this hypothesis, the co-articulation we report would arise from an interaction between the execution dynamics associated with the current movement and the planning dynamics of the second planned movement. An alternative hypothesis is that the preparation processes of the next two movements directly interact with each other, and possibly are even encoded in partly together (Fusi et al., 2016; Rigotti et al., 2013). Our results are more suggestive of the latter since we observed no coarticulation when the next target was only available during execution of the current reach (**Figure 5D, H2**). Nevertheless, careful electrophysiology experiments are necessary to investigate the exact mechanism by which planning processes interact. The current paradigm provides a useful framework to do so.

Methods

Participants

Ten participants (4 female) with an average age of 24 years (4.24 SD years) completed seven experimental visits for this study (~10 hours data collection per participant). They were all right-handed with average handedness of 78 (24 SD), measured by the Edinburgh Handedness Inventory. The participants reported no prior history of musculoskeletal, neurological, or psychiatric disorders. All the participants provided informed consent in the first session, and they were remunerated CA$ 15 per hour in the seventh and last session of the study. All the procedures were approved by the Health Sciences Research Ethics Board at the University of Western Ontario.

Apparatus

Participants performed all experimental trials in an exoskeleton robot, (Kinarm, Kingston, ON). The participants were seated on a height-adjustable chair while their right arm rested comfortably on the robot arm, which supported the elbow and shoulder weight against gravitational force and allowed them to freely move their hand in the horizontal plane. Arm kinematics were recorded at 1000 Hz. All the reaching targets were presented by a horizontally placed monitor onto a mirror which occluded the vision of the participant's arm (Figure 1A).

General Procedures

In each experimental trial, participants performed sequences of 14 reaches. The sequences were generated from a hexagonal grid of equidistant circular targets (see **Figure 1A-B**). The radii of the targets were 1 cm, and the center of neighboring targets were 4 cm apart. The participants' arm was occluded - they only saw a circle with radius of 0.5 cm aligned with the tip of their index finger as their hand feedback. The sequences always started from a fixed home target in the center of the working space. We generated sequences according to two rules. First, the next target in the sequence should be a neighbor of the previous target. This ensured that all the reaches were 4 cm apart. Second that there were no loops smaller than 5 reaches. This ensured that, when multiple future targets were presented, they did not overlap. The participants were instructed to move their right hand in the home target to start a trial. Once the hand was in the home target, either one, two, three, four, or five future targets of the sequence appeared on the screen (depending on the horizon condition); brightness indicated the order of targets, with the brightest target being the immediate next target. The participants were instructed to stay in the home target for 300 ms, after which they received a go cue by the disappearance of the home target. The participants were instructed to always move their hand to the brightest target and stay in the target until it was “captured”. Once one target was captured, the captured target disappeared, the brightness of the targets was updated, making the next target the brightest, and a new target appeared at the end of the horizon. This process was repeated until all 14 targets were captured. If the participant failed to stay in the target for the dwell time or the initial wait time in the home target, the trial was interrupted with and error message and rejected. Interrupted trials were repeated later in the session.

The design manipulated two parameters: how much time participants had to stay in each target to capture it (dwell time), and how many future targets were on the screen (horizon). The dwell times could be 75 ms, 200 ms, or 400 ms. In the horizon conditions, (H1-H5) 1-5 future targets were visible. In the case of H1, the task is reduced to a sequential reaction time task, and with longer horizons, participants could potentially plan multiple future movements ahead of time.

The entire experiment had 7 sessions. The first 5 sessions were designed to get a time and curvature analysis in all Dwell and horizon conditions. The last two session added the jump experiment.

Time and Curvature Analysis

The first 5 sessions measured performance in 15 conditions (3 dwell times x 5 horizons). Each session consisted of three blocks of 120 trials for each dwell time, and the horizon was randomized across trials totaling 360 trials per session. The order of dwell time blocks was randomized across five sessions for each participant. Each session of data collection was 1 hour and 15 minutes on average. As the first step, for each trial, we broke down the full sequence of reaches to their constituting single reaches by segmenting the full sequence trajectory whenever a target was captured. This led to a set of 14 individual reaches starting from each target and ending in the next. For all the analysis we were interested in simultaneous planning and execution processes, therefore we excluded all targets that were visible in the beginning and could therefore be preplanned. We also excluded 1-5 targets at the end of each sequence since there was no need to plan future targets anymore. The number of excluded reaches changed with the Horizon. For instance, in the H1 condition, we excluded the first and the last reach in the sequence.

Given our hexagonal grid, for each reach, there could be a maximum of 5 potential next target positions. However, near the boundaries of the workspace, the number of potential next targets decreases so the participants could potentially predict the overall position of the upcoming target and plan for it ahead of time (Glaser *et al.*, 2018). To ensure that this possibility did not affect our results, we only considered reaches with five potential future choices. This excluded the reaches towards and parallel to the boundaries of the workspace.

For the analysis of movement time, we computed inter-reach interval (IRI), defined as the time the hand entered a one target until it entered the next one. We subsequently averaged IRI values across all the reaches of a trial, all trials, and all sessions of each participant. The IRI contains both the time that the hand passed through the target and the time that the hand was moving between the two targets.

For the curvature analysis, we assessed the effect of the position of the +2 target on the curvature of the reach towards the +1 target. We started by aligning all the reaches: First, we translated the position of the +0 target (where the hand is sitting), the -1 target, the +1 target, and the reach trajectory so that the position of the +0 target is set to the center of the 2D coordinate system (0,0) cm. This ensures that all the reaches start from the same position. Next, we rotated the targets and trajectory around the +0 target so the position of the +1 target rests at (4,0) cm coordinates. This ensures that all the reaches have the same directions. With these transformations, the angle of the line connecting the +1 target to the +2 target, relative to the horizon line, connecting the +0 target to the +1 target, can be either -120, -60, 0, 60, or 120 degrees. The same is true for the angle of the line connecting the -1 target to the +0 target.

Next, we quantified the curvature of +1 reach. We used all the translated and rotated reaches of all the participants. To make the length of the reaches equal, for each reach, we took 100 equally distant spatial samples along the horizontal line connecting the center of the start target to the center of the end target of the reach. Then, we performed a PCA on the matrix containing the y coordinate values of each reach. The size of this matrix was (# reaches x 100). The first and the second PCs were arc-shaped and S-shaped “eigen reaches” each accounting for 72% and 17% of the total variance. We then projected each reach onto the first eigen reach and used the resultant scalar value as a measure of curvature. The absolute value of this scalar shows the amount of the curvature, and the sign indicates the direction of the curve. We used all the reaches of all the participants to calculate the PCs, and then for each participant and condition, the curvature value was calculated separately. This ensured that the comparison between the conditions and averaging across participants are meaningful.

Finally, we were interested in the effect of the +2 target angle on the curvature of the reach to the +1 target. However, the curvature of a reach in a sequence also depends on the previous reach, therefore, to account for this effect, we fitted a linear model that predicted the signed curvature value of each reach based on the position of the previous target (angle of -1 target), next target (angle of +2 target). The angles were one-hot coded, resulting in one regressor for each angle; therefore, the beta values represent the effect of each input angle onto the curvature effect. This process was performed for each of the Dwell Time and Horizon conditions separately. Finally, as summary statistics for the effect of all the one-hot coded values the outgoing target (+2 target effect), we fitted a line to beta values for each of the five angles. We used the slope of this line as a summary of the overall effect. Zero slopes indicated no curvature effect, the value and sign of the slope show the strength and direction of the effect, with a negative slope showing curvature towards the opposite direction of the next target, and vice versa.

Jump Experiment

For the last two data collection sessions, we focused on the 75 ms dwell condition and two of the horizons (H2, H3). All other parameters including the grid of targets, length of the sequence, size of the targets, etc. were identical to the first five sessions. In these experiments, only one jump of a target could happen in each trial. The jump happened randomly between the 4th to 10th reach of the sequence. We interleaved many no-jump trials in these sessions to avoid anticipation or adaptations for the jumps. The order of these two last sessions was randomized across participants. The +1 jump experiment consisted of 400 trials, 200 target jumps in H2 and H3, interleaved with 200 no jump trials with randomized across horizons. In the case of a jump trial, we displaced the next target (+1 target) exactly when the current target (+0 target) was captured. Before the jump, a pre-jump +1 target was shown on the screen, and then, at the moment of the jump, that is when the 75 ms Dwell time was satisfied and the current target (+0 target) was captured, we removed the pre-jump +1 target and a new +1 target appeared on the screen. Both the new and pre-jump +1 target were selected in a way that was compatible with the current position of the +2 or +3 targets on the screen, in other words, the jump was compatible with the rules of generating sequence in the task. This jump happened both in the context of Horizon 2, with two future targets, and in Horizon 3, with three future targets presented on the screen.

The +2 jump experiment was performed only in Horizon 3 (H3) condition. There was a total of 300 trials. Two-third of them were no jump; in the remaining one-third, exactly at the movement that the current target (+0 target) was captured, the second future target (+2 target) jumped to a new position, and the position of the next target (+1 target) remained unchanged. Before the jump, we showed a temporary +2 target (pre-jump +2 target) on the screen, and the jump happened with the disappearance of the pre-jump +2 target and the appearance of a new target as the new +2 target.

Statistical Analysis

We employed a within-subject design. All the analysis were performed in R Studio 22.07.1. For analysis of IRI and curvature effect, we used two-way repeated measures ANOVA. Factors were Dwell time (3 levels), Horizon (5 levels: H1-5), and (Dwell Time x Horizon) interaction. For comparison between different levels of each significant factor, we adjusted p-values for multiple comparisons using Holm method. For the jump +1 target experiment, we used a repeated measures two-way ANOVA with jump (2 levels) and horizon (2 levels) as factors. Correction for multiple comparisons was similar to the IRI analysis. The details of statistical analysis including the degrees of freedom, the test statistic, and the p-value are provided in the text.

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