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Modulating Fitts's Law: Perceiving targets at the last placeholder

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ABSTRACT

Fitts's Law predicts increasing movement times (MTs) with increasing movement amplitudes; however, when targets are placed in a structured perceptual array containing placeholders, MTs to targets in the last position are shorter than predicted. We conducted three experiments to determine if this modulation has a perceptual cause. Experiment 1, which used extremely diminished (three pixel) placeholders, showed that the modulation is not due to perceptual interference from neighboring placeholders. Experiment 2, which measured reaction times using a target detection task, showed that the modulation does not result from speeded perceptual processing at the last position of the array. Experiment 3, which measured accuracy using a masked letter-discrimination task, showed that the modulation does not result from the increased quality of perceptual representation at the last position of the array. Overall, these findings suggest that the changes in effectiveness of visual processing (less interference, speeded processing, and increased quality) at the last position in the perceptual array do not drive the modulation. Thus, while the locus of the Fitts's Law modulation appears to be in the movement planning stage, it is likely not due to perceptual mechanisms.

We all have an intuitive awareness that many of our actions are constrained by a tradeoff between speed and accuracy. In terms of limb movements, this fundamental tradeoff was originally quantified by Paul Fitts in 1954. Fitts described the movement time [MT] required to reach an object as the logarithmic function of the target's index of difficulty [ID], which is made up of the distance to the target (A), and the width of the target (W), [ID = 2A/W], such that MT = a + b[log2(ID)], where a and b are empirically observed constants. That is, Fitts predicted that it will take longer to reach an object which is far away and small (i.e., an object with a large index of difficulty) than an object which is close and big (i.e., an object with a small index of difficulty). Fitts's formula has proven to be so robust that it has become ubiquitously known as Fitts's Law and is now entrenched in the literature as one of the few laws of human behavior.

It has recently been found, however, that when targets are placed in a structured perceptual array, MTs to targets in the last position of the array are shorter than predicted by Fitts's Law (Adam, Mol, Pratt, & Fischer, 2006).The perceptual array is created by square placeholder boxes that denote the location where the target might appear (see the inset in Fig. 1). In other words, when allocentric information (the placeholders) marks the potential target positions, targets with the highest IDs no longer produce the longest MTs. Moreover, targets with identical IDs (i.e., same distance and size) produce different MTs depending on whether the target is in the middle or last position in a placeholder array (Pratt, Adam, & Fishcher, 2007). These two studies clearly show a modulation of Fitts's Law.

In order to determine how the array of placeholders is able to modulate the planning and control of goal-directed actions, Fischer, Pratt, and Adam (2007) presented the array of placeholders either at the same time that the target appeared or when the movement to the target was initiated (placeholders always present or always absent were also conditions in the study). The authors found the Fitts's Law modulation when the placeholders were always present and when they appeared at target onset, while a standard Fitts's Law MT function was found when the placeholders were absent and when they appeared at movement onset. Based on these results, Fischer et al. concluded that the modulation of Fitts's Law occurs in the planning stage of rapid aimed limb movements and not in the online control stage. This conclusion was supported by Bradi, Adam, Fischer, and Pratt (2009), who removed the placeholders at target onset or movement onset, and found that the modulation occurred only in the latter condition (i.e., when the placeholders were visible during movement planning). Perhaps the strongest evidence for localizing the modulation to the movement planning stage comes from Radulescu, Adam, Fischer, and Pratt (2010) as they found that the Fitts's Law modulation also occurs with imagined movements. Here, subjects were asked to place their finger on the home position, to imagine moving to the target when it appeared, and to lift their finger off the home position when

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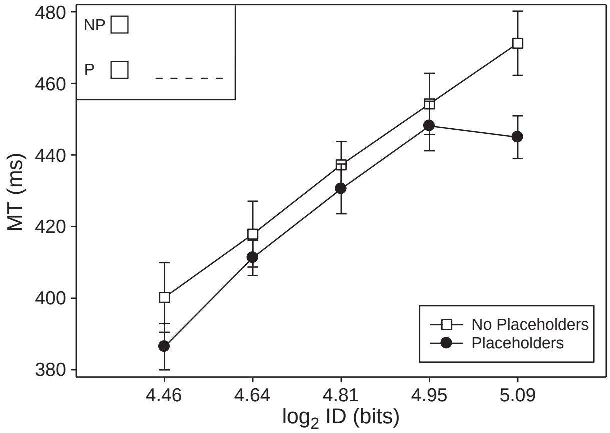

Fig. 1. Mean movement times (MTs) for movements to targets at each of the five positions for placeholder and no-placeholder conditions for Experiment 1. MT to the last position is shorter in the placeholder condition than in the no-placeholder condition; a modulation of Fitts's Law. Error bars are 95% confidence intervals with between-subject variance removed (Cousineau, 2005). The top left corner inset is a schematic (not to scale) showing the location of the placeholders in the two experimental conditions; NP = the no placeholder condition, P = the placeholder condition.

the imagined movement was complete. Imaginary MT was measured as the difference between target onset and finger uplift, and imaginary movements produced patterns of MTs that were nearly identical with those produced by real movements, including the modulation of Fitts's Law. Taken together, these findings indicate that the effect of the placeholders occurs when the movement is being planned and is not dependent on online control or feedback-based corrective movements.

While there is strong evidence that the modulation of Fitts's Law is localized in the planning stage, little is known about the actual mechanism(s) that cause this modulation. One possibility is that the modulation results from an effect on the perceptual system. That is, the presence of placeholders may alter the perceptual processing of targets, and the previously reported changes in movement time reflect a downstream consequence of this perceptual effect. To test this possibility, in the present study we evaluated whether structured arrays affect perceptual processing. Specifically, two possible perceptual causes for the modulation will be examined. The first cause can be described as perceptual interference; targets at the middle positions in the placeholder array are bounded by other placeholders, while targets at the end positions are bounded by only a single placeholder. Given that targets bounded by more visual information are more difficult to perceive than targets bounded by less information (Bouma, 1970), it may be that the modulation is due to middle targets producing longer than expected MTs rather than end targets producing shorter than expected MTs. If perceptual interference plays a role, then two predictions follow: targets at first positions should also show an MT advantage, and MTs for middle targets positions should be slower in placeholder present conditions than placeholder absent conditions. None of the previous investigations of the modulation of Fitts's Law explicitly examined this issue, but circumstantial evidence from these studies breaks both ways. To the first prediction, while first locations did have shorter MTs in Pratt et al. (2007), none of the other studies has shown this effect. To the second prediction, while Fischer et al. (2007) and Bradi et al. (2009) did find overall longer MTs when the placeholders were present, in Adam et al. (2006) MTs to the middle locations in the present and absent conditions were virtually identical. Overall, the pattern of results from the existing studies is equivocal in terms of the role of perceptual interference.

The second possible perceptual cause for the modulation of Fitts's Law can be described as perceptual salience: In a linear array of objects, end positions may simply be more salient than other positions. It is well known that when visual stimuli are crowded together (i.e., they appear in close proximity to each other) perception of any one stimulus is impaired (e.g., Bouma, 1970; Pelli, Palomares, & Majaj, 2004). But crowding effects weaken when the target stimulus stands out from the neighboring stimuli (Saarela, Sayim, Westheimer, & Herzog, 2009), and end positions in linear arrays seem likely to stand out given that visual information is concentrated at contours and terminations (e.g., Biederman & Ju, 1988). Given that "… the more conspicuous the object, the greater its representation, and the more likely it will be chosen" (Fecteau & Munoz, 2006, page 1364), the MT advantage for the last position targets may occur because the representation of that position is prioritized for planning the movement. If this is indeed the case, presumably there would be several consequences on movements to end positions in arrays: shorter movement times, shorter reaction times, and less endpoint variability. The shorter MTs are well-documented, but none of the previous studies has shown conclusive results with regard to RTs. It should be noted, however, that none of the studies stressed initiating the movements as quickly as possible. In terms of variability, Adam et al. (2006) showed a decrease in constant error (i.e., less undershoot) for targets at last positions, and Al-Aidroos, Fischer, Adam, and Pratt (2008) found a decrease in the end-point variability of saccadic eye movements, but other studies (Pratt et al., 2007; Fischer et al., 2007) did not report similar findings. As before, the pattern of results across the studies is equivocal with regard to what role perceptual quality might have in modulating Fitts's Law.

Given there are bits of evidence for and against both the possibility of perceptual interference (at the center of perceptual arrays) and perceptual enhancement (at the edges of perceptual arrays), the present study was designed to explicitly test these factors. Experiment 1 focuses on perceptual interference while Experiments 2 and 3 focus on perceptual enhancement.

1. Experiment 1: Minimal placeholders

In most previous experiments showing the modulation of Fitts's Law, the placeholders were 10 × 10 mm outline boxes (25 by 25 pixels)separated by 10 mm. This means that the edge of one placeholder was quite close to the edge of its neighbors. When a target is surrounded by placeholders indicating other potential target locations, there is competition from those neighboring placeholders for the response (Tipper, Lortie, & Baylis, 1992; Keulen, Adam, Fischer, Kuipers, & Jolles, 2002), and thus movements to middle targets may be biased toward accuracy whereas end targets, with less interference from a single neighbor, may be biased toward speed. To test this account, we used what has become the standard design for modulating Fitts's Law (five horizontally aligned locations with placeholders either present or absent) but we modified the placeholders. Unlike the boxes from our previous experiments, here we used a much reduced amount of visual information to mark potential target locations — a line one pixel high and three pixels long. If perceptual interference is a factor in modulating Fitts's Law, the modulation should not be present with such minimal placeholders.

1.1. Method

1.1.1. Subjects and apparatus

Sixteen University of Toronto undergraduate students (mean age: 19 years, 7 females) took part in Experiment 1 in exchange for partial course credit. All subjects reported to be right handed and to have normal or corrected to normal vision. The experiment was conducted in a dimly lit, sound-attenuated testing room on a 21-inch ELO touch screen. The touch screen was angled backwards (15°) to make movements more comfortable.

1.1.2. Procedure and design

The experiment had two conditions: placeholders and no-placeholders. The home position was a white box (10 × 10 mm) and the five placeholders (each a single white horizontal line 1 pixel high and 3 pixels long) were located to the right of the home position (center to center from the home position: 110, 125, 140, 155, and 170 mm, corresponding to ID values of 4.46, 4.64, 4.81, 4.95, and 5.09 bits, respectively). These placeholders were centered at the same location as the bottom line of the square placeholders used in previous studies (e.g., Radulescu et al., 2010). The target (a filled-in square of 25 × 25 pixels) was green and the background was black. To start each trial, subjects placed their right index finger in the home position. Once their finger was correctly placed inside the home position the lines above and below the home position disappeared and, following a random interval of between 500 and 1000 ms, the target appeared. The subjects were instructed to lift their finger from the home position and move it as quickly and as accurately as possible to the target position. If the subject's finger landed outside the target position a brief error tone was presented and the trial was tagged as an error. MT was defined as the time between when the subjects lifted their finger from the home position to when they placed the finger on the target. Placeholder and no-placeholder conditions were identical except that in the no-placeholder condition the 3-pixel placeholders were not present. The experiment consisted of two blocks of 125 trials each (25 trials for each target position), with one block having placeholders and the other no-placeholders. The target position was randomized within each block and the blocks were counterbalanced across subjects.

1.2. Results and discussion

Mean MTs (see Fig. 1) were analyzed with a 2 (placeholder: present or absent) by 5 (target position) repeated-measures analysis of variance (ANOVA). There was a significant main effect of target position, $F(4, 60) = 47.08$, $p < .001$, as MTs increased with the distance from the home position to the target position. However, there was no main effect of placeholder condition $F(1, 15) < 1$, nor an interaction effect, $F(4, 60) > 1.8$, $p > .14$, as the MTs for the first four target positions were virtually identical across placeholder present and placeholder absent conditions. Importantly, an a priori t-test indicated that the MT for the last position in the placeholder present condition was shorter than for the placeholder absent condition, $t(15) = 2.33$, $p < .035$. The same modulation of Fitts's Law observed with the full square placeholders by Adam et al. (2006), Pratt et al. (2007), Fischer et al. (2007), Bradi et al. (2009), and Radulescu et al. (2010) was replicated with placeholders only three pixels in size. Analyzing the linear and quadratic contrasts verifies the modulation, as the placeholder condition had both significant linear, $F(1, 15) = 41.195$, $p < .001$, and quadratic, $F(15) = 11.27$, $p < .004$, trends while the no-placeholder had significant linear, $F(15) = 40.739$, $p < .001$, but not quadratic, $F(15) < 1$, trends. Moreover, the modulation cannot be attributed to wider effective target widths (W_e; all $Fs < 1$; see Fig. 2, which also shows average velocities).Thus, perceptual interference from adjacent placeholders does not appear to be necessary for generating a modulation of Fitts's Law.

2. Experiment 2: Target detection

In Experiment 2 we tested whether or not the modulation of Fitts's Law results from a speeding of perceptual processing at the final position in perceptual arrays. While measures of response speed (i.e., RT) were collected in previous Fitts's modulation studies, these previous studies are not well suited to assess changes in perceptual processing. First, in these prior studies responses were not speeded: subjects were told to move as quickly and accurately as possible, but could take as long as needed to initiate the movement. Second, subjects made motor movements that varied with target position and, therefore, RT does not provide a pure measure of perceptual processing, but also motor program selection. Accordingly, the

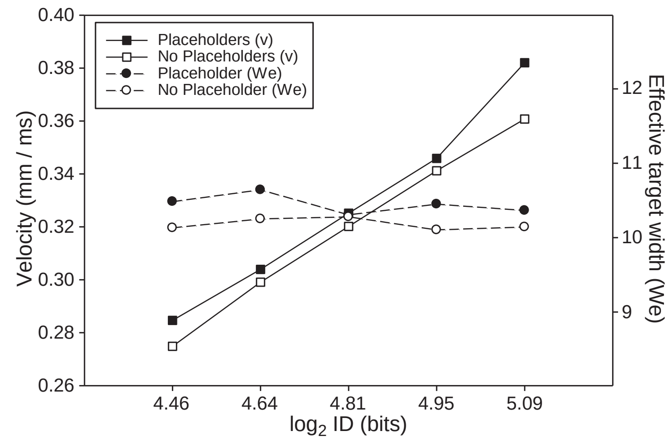

Fig. 2. Average velocity profiles (v) and effective target widths (W_e) at each of the five positions, for both conditions in Experiment 1. W_e was calculated as 4.133 × SD of the horizontal endpoint (Welford, 1968).

standard Fitts's modulation task was modified in Experiment 2 in two ways: responses were speeded, and subjects performed a target detection task in which they pressed a single button when the target appeared (regardless of position). In addition, we used the three pixel placeholders, which produced a robust modulation in the previous experiment, because these minimal placeholders generate very little visual interference between target locations.

2.1. Method

2.1.1. Subjects and apparatus

Using the same apparatus as Experiment 1, 19 new University of Toronto undergraduate students (mean age: 19.1 years, 11 females, all reporting normal or corrected to normal vision) were tested in Experiment 2.

2.1.2. Procedure and design

The display was identical with the one used in Experiment 1, only in this experiment the subjects were asked in both conditions (placeholders vs. no-placeholders) to press the spacebar key as soon as they noticed the target appear. Subjects were also instructed to maintain fixation on the home position, a cross of the same height and length as the square home position in Experiment 1, throughout the duration of each trial. The experiment had 500 trials, separated in two blocks of 250, 50 trials at each position, with one block having placeholders and the other no placeholders. The target position was randomized within each block and the blocks were counterbalanced across subjects.

2.2. Results and discussion

Mean RTs (see Fig. 3) were analyzed with a 2 (placeholder: present or absent) × 5 (target position) ANOVA. Premature responses (RT < 100 ms) and RTs longer than 2000 ms, less than 2% of all responses, were removed prior to data analysis. There was not a significant main effect of target position, $F(4, 72) < 1$, as RTs did not increase with target distance. There was also no main effect of condition, $F(1, 18) < 1$. Moreover, there was no interaction effect between the condition of the experiment (placeholder vs. no-placeholder) and target position $F(4, 72) < 1$. Finally, RTs for the last position in the array were almost identical between placeholder conditions, $t(18) < 1$. Therefore, the Fitts's Law modulation did not extend to RTs in a target detection task, indicating that speeded perceptual processing at the last position of perceptual arrays does not drive the modulation.

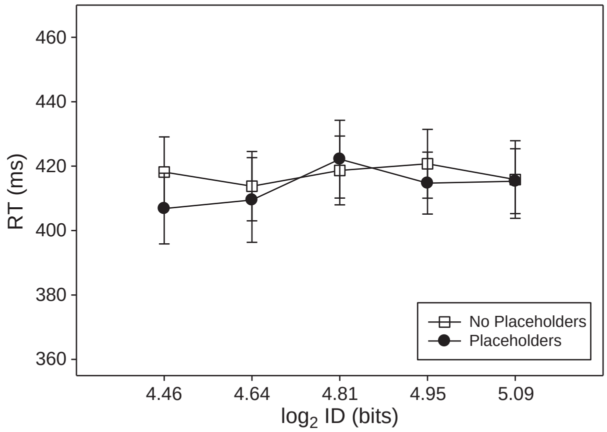

Fig. 3. Mean reaction times (RTs) to target onsets at each of five positions for both conditions in Experiment 2 are shown. Error bars are 95% confidence intervals with between-subject variance removed (Cousineau, 2005).

3. Experiment 3: Target identification

Although Experiment 2 showed that the speed with which stimuli are detected at the last position in the array is not enhanced by placeholders there is still the possibility that the target is perceived more accurately when it is presented at the last position, and this results in a more effective target representation for movement planning. To test this hypothesis we created an object recognition task by replacing the previously used target, a green square, with one of two possible letters, and asked subjects to discriminate the identity of the target. Similar tasks have previously been used to measure changes in perceptual quality (e.g., Prinzmetal, McCool, and Park, 2005; Stevens, West, Al-Aidroos, Weger, & Pratt, 2008).

3.1. Method

3.1.1. Subjects and apparatus

Using the same apparatus as Experiments 1 and 2, 12 new University of Toronto undergraduate students (mean age: 19.4 years, 8 females, all reporting normal to corrected to normal vision), were tested in Experiment 3.

3.1.2. Stimuli, procedure and design

In the current experiment the target was either the letter “F” or “T” (Helvetica font, size 21); otherwise the display was identical with the one used in Experiment 2. Subjects were asked to fixate on the fixation cross, and between 500 and 1000 ms later, the target appeared. The target was displayed for 50 ms and then masked by the letter “O” (Helvetica bold, font size 21 points). All stimuli appeared in white on a black background. The subjects were instructed to respond to the identity of the target letter; if it was an “F”, they were to press the “z” key on a standard keyboard, if it was a “T” they were to press the “/” key. Subjects were also instructed to respond to the target before a timeout of 2000 ms while maintaining accurate performance. Following any incorrect responses, an error feedback was provided by a tone (200 Hz).

During the entire trial the subject was required to remain fixated on the fixation cross. A closed circuit camera feed of the subject's eyes was used to ensure task compliance. Task difficulty was adjusted for each subject to avoid ceiling and floor effect. Specifically, the experiment began with 80 titration trials; after every 8 trials the size of the target was adjusted: if the subject achieved more than 6 correct trials the size of the target was decreased by one font size, e.g. from 21 to 20 points, and if the subject achieved fewer than 6 correct trials the font size was increased by one font size (resulting in a mean font size of 23 points, SD 3.2). The experiment had 50 trials at each target position, for a total of 250 trials per placeholder condition.

3.2. Results and discussion

Accuracy (proportion of correct responses) was analyzed with a 2 (placeholder condition: absent or present) by 5 (position) ANOVA. Overall there was no main effect of condition, $F(1, 11) < 1$. There was, however, an effect of position, $F(4, 44) = 63.7$, $p < .001$: accuracy decreased considerably as the targets appeared farther away from the fixation cross, reflecting diminished visual acuity with increasing retinal eccentricity (see Fig. 4). There was also no interaction between placeholder condition and position, $F(4, 44) < 1$. Importantly, the proportion of correct responses for the last target position was not statistically different between the conditions (placeholder vs. no placeholder), $t(11) < 1$. Therefore, the findings from this experiment indicate that the Fitts's Law modulation is not driven by enhanced perceptual accuracy at the last position in the array.

4. General discussion

In the current study we examined possible perceptual contributions to the Fitts's Law modulation, according to which the last position in a visually structured array produces shorter than predicted MTs. Experiment 1, which used minimally visible placeholders, replicated the basic modulation with MT, showing that possible interference from the other placeholders in the previous studies (e.g., Adam et al., 2006; Pratt et al., 2007) was not the cause of the modulation. Experiment 2, which measured RTs, showed that subjects are not faster in detecting targets appearing in the last location than they are detecting targets appearing at the other positions. Experiment 3, which measured letter discrimination accuracy, showed that targets presented at the last position in the array are identified equally accurately in both placeholder present and absent conditions. With three major perceptual effects eliminated, the findings from the present study point to the conclusion that perceptual factors may not play a role in the modulation of Fitts's Law.

Having eliminated placeholder interference, improved target detection, and improved target discrimination at the final position in the perceptual array as potential driving causes, the locus of the modulation of MTs appears to be based in the motor system. Moreover, the present study confirms the robustness of the effect; the modulation was found with placeholders that each occupy only a sliver of the display. While the results of Fischer et al. (2007), Bradi et al. (2009), and Radulescu et al. (2010) clearly implicate the

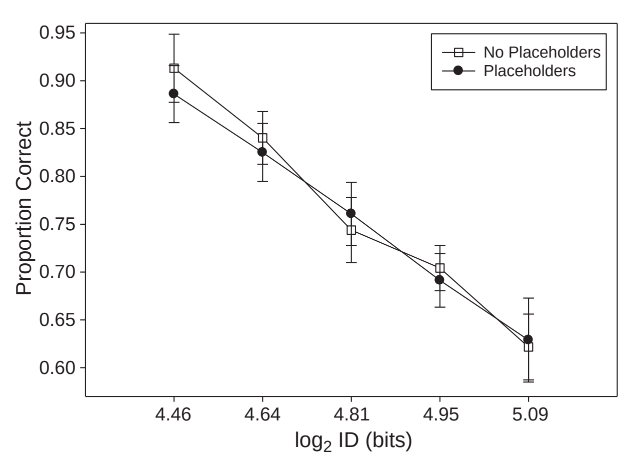

Fig. 4. Mean accuracies (proportions of correct responses) at each of five positions for both conditions in Experiment 3 are shown. Error bars are 95% confidence intervals with between-subject variance removed (Cousineau, 2005).

planning stage of motor programming, pinpointing the exact underlying mechanism remains elusive. One possibility is that the effectiveness of the motor program for the last position in the array is enhanced. For example, it could be that when subjects have higher velocities moving to the last position, they may decelerate later—thus moving at greater speeds for longer than when they are moving to any other position in the array. This mechanism is impervious to detection by rough measurements of MT and requires kinematic analysis of the movements. Therefore, future experiments should include such tasks and measurements that would permit a careful kinematic analysis of movements to targets in structured visual arrays.

The finding that even very minimal placeholders still induce a modulation of Fitts's Law is interesting given the previous work on target spacing with guided limb movements. Keulen et al. (2002), following up on the action-based attention work initiated by Tipper, Lortie, and Baylis (1992), found interference from distractors when the target positions (denoted by placeholders) were close together (5 positions across 70 mm, 5 mm between placeholders) but not when the target positions were far apart (5 positions across 130 mm, 20 mm between placeholders). The minimal placeholders used in Experiment 1 of the present study were nearly 15 mm apart from each other, which suggests that the spacing of the target positions rather than the density of the placeholders in the target position array is the critical factor in distractor interference. Thus, for the modulation of Fitts's Law to occur, it seems that two conditions must be met: (1) target positions must not be too far apart in the array, and (2) some visible marker of those positions must be present.

The findings that the last placeholders did not produce any effects on the perceptual detection and discrimination tasks indicates that the quality of the representation of the last target location is not improved by the presence of the perceptual array of placeholders. Of course, pointing responses rely on spatial information regarding targets, and it is possible that modulations of that type of information are not readily picked up by detection and discrimination tasks. In other words, it is possible that the improved salience of the last placeholder does improve the quality of the representation of that position, but that change in quality is specific to information used by the motor system, and can presumably only be measured in tasks involving spatially-based motor responses. Nevertheless, Experiments 2 and 3 of the present study eliminate the possibility that improved salience at the last array position results in a general improvement in the acquisition of perceptual information from that position. In other words, while the mechanism underlying the modulation of Fitts's Law remains unknown, it seems that this mechanism is firmly rooted in the motor system.

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