UNIVERSITY OF PADOVA

Department of General Psychology

Bachelor's Degree Course in Techniques and
Methods in Psychological Science

Final dissertation

From Number to Action: Exploring 3D Motion Analysis and Mental Number Line

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Abstract

The mental number line (MNL) is a form of spatial numeric representation that associates small and large numbers with the left and right space, respectively. Most scientific studies focus on response times, but motor patterns while responding to numbers can provide insight into cognitive representations. A new study investigated the influence of number processing on motor responses. Participants were presented with numerical or non- numerical stimuli and instructed to kick a small ball with their right index toward a soccer goal. The main finding was that kicking after observing a larger digit changed the temporal aspects of the movement; in particular, it extended the time in which the index reached maximum acceleration. This result shows a relationship between the magnitude of the observed experimental stimulus and the extension component of the movement.

1. Introduction

One essential feature of the human cognition system is the propensity to encode environmental information spatially (Gevers et al., 2003). The spatial organization of numbers follows a continuum oriented from left to right (Fias & Fischer, 2005; Bueti & Walsh, 2009; Dehaene, 2011). The fundamental theory behind this spatial-numerical association was first proposed by Galton in 1880. According to his theory, people perceive and categorize numbers as progressive spatial arrangements from left to right along a Mental Number Line (MNL), with the smallest number on the left and the highest on the right.

Dahaene initially observed this spatial representation of numbers in 1993, which was the first scientific evidence. The Spatial Numerical Association of Response Codes (SNARC) effect was named after him when he discovered in one of his research projects that people respond more quickly to more significant numbers on the right side of space and lower numbers on the left. Adults naturally activate an internal representation of a directed spatial continuum when recognizing or comparing numbers (Dahene et al., 1993). After this evidence was found, numerical cognition representation was investigated from multiple perspectives.

The effect of culture on the MNL can be seen by how the orientation is affected, considering that left-to-right line orientation is reduced in the right-to-left reading cultures (Zebian, 2005; Shaki & Fischer, 2008; Shaki et al., 2009).

When pointing at the middle of a series of repeated “1”s, people exhibit leftward bias; when the sequence consists of “9”s, they exhibit a rightward bias (Fischer, 2001). Rugani et al. (2018) state that left or right space is automatically activated while processing numbers. Processing smaller numbers pre-activates left space, and processing vast numerical information pre-activates right space.

Another idea proposes that the size of the numerical input impacts both the frequency and direction of decision; this has been backed up by a substantial amount of research showing that numerical processing can alter response time, but there are fewer ones focused on the impact of numerical processing on response selection. Daar and Pratt (2008) explored this aspect using a free response task. During their experiment, participants were told to push any of the two buttons on the keyboard (left: z, right: /) as soon as the stimulus went from white to green in the middle of the screen. The stimulus could have been a neutral character (&, *, @, #), a small number (1 or 2), or a large number (8 or 9). Consequently, each participant was invited to hit the button of their choosing. The experiment’s findings demonstrated that when faced with small numbers, participants clicked the left button more frequently, while when faced with high numbers, they touched the right button more frequently.

Fischer carried out an experiment in 2014 to investigate the relationship between mental number representation and a real-world setting. During the first experiment, participants were asked to walk and generate random numbers; on average, they produced lower numbers more often when they were about to make a left turn. During the second experiment, participants were asked to listen to a series of numbers and quickly turn to the left or right. According to the experimenters ' findings, when listening to a smaller number of stimuli, participants tended to turn more to the left (Shaki & Fischer, 2014).

During Lindemann and colleagues' experiment in 2007, participants were instructed to make two distinct reaching and grasping motions toward a target item to indicate whether an Arabic digit was odd or even. The object was made up of two parts: an upper section, a small cylinder with a diameter of 0.7 cm, that was bonded to the center of the lower part that was made up of a large cylinder with a diameter of 6 cm. while the smaller part needed precise grasping with the thumb and forefinger in opposition, the larger part required grasping with the entire hand. The target object was positioned behind an opaque screen on the right side of the table so participants could easily reach it with their right hand without receiving any visual cues. For the even numbers, half of the participants had to execute a precision grasp; for the odd digits, they had to execute a full-hand grip; and for the other half, the opposite was true. Participants were requested to hold off on responding whenever the no-go condition was presented; this was implemented to prevent reaching motions before the number was processed and the parity judged. When faced with small numbers, precision grasping actions started more quickly, but full-hand grasping movements started more quickly when faced with big numbers.

Furthermore, the kinematics of grip opening were influenced by the magnitude of the number stimulus: when participants held the large object associated with high numbers, their maximum hand opening was greater than when they had to grasp the smaller object associated with small numbers. Consequently, these findings imply that a generalized system for the representation of numerical magnitude shares standard codes with the representation of numbers and actions (Lindemann et al., 2007). This makes the relationship between numbers and movements clear. This link is evident in everyday activities as well as in scientific research.

Kinematic analysis has been defined as a tool for describing motion independent of the internal and external forces that cause it (Castiello et al., 1995).

In kinematic analysis, specific aspects must be chosen and verified under various experimental situations to explore the fundamental movement mechanisms. These factors could include the length of the movement, precision, and angular changes of the body’s numerous joints (Castiello et al., 1995). Thus, the center of gravity, acceleration, and velocities of the entire body or specific body segments, such as the trunk or upper limb, are all considered while analyzing human movement in kinematics.

Optoelectronic devices are one of the various kinematic measurement techniques that have advanced significantly. One of the system's most notable features is the ability to apply active or passive markers to the subject that the cameras can detect directly. According to Castiello et al. (1995), active markers are light-emitting diodes that emit infrared rays and are connected to a control unit via a convoluted network of wires on the participant. In contrast, passive markers are plastic spheres or hemi-spheres coated with reflective material, which are directly placed on participant’s skin. Infrared light is then directed at the participant, and the light reflects off the markers, allowing multiple cameras to capture their positions. For accurate detection, these cameras must be strategically placed around the participant so that each marker is visible to at least two of them. The sampling frequency can range from 50 to 250 Hz, allowing the device to follow changes in marker location while producing a sufficient capture of the overall movement pattern. The system's accuracy depends on human intervention to verify that the computer correctly determines which marker belongs to the hand and which to the ball or goal or on high-quality computer software capable of processing the incoming data.

2. Experimental hypothesis

The experiment described in this thesis attempted to replicate and extend the study conducted by Rugani and colleagues (Rugani et al., 2018), which examined even numbers to assess the influence of culturally ordered values on the mental number line. This experiment used odd-number stimuli and examined possible parallels or distinctions between the mental representation of odd and even numbers. Moreover, the purpose was to confirm if the number-space association was limited to number stimuli or applied to additional categories of culturally structured values; this was done through movement analysis. The alphabet's letters were selected as stimuli to investigate this, namely, the first and last letters linked to an alphabetic intermediate letter (stimuli A, M, Z). Any variations in pitch between the alphabetic and numerical stimuli were noted. Finally, this study attempted to see if there were any changes in the kinematics of the individuals' motor activity by reducing the numerosity between stimuli small and big while keeping differentiation in firing with stimuli S1, S3, S5, S5, S7, S9.

Because the usual metrics used to describe the reaching component mainly focus on trajectory and speed, we anticipate that a functional association between numerical cognition and action planning will present itself in various spatiotemporal patterns. The two characteristics of numerical priming (spatiality—smaller numbers are associated with left space and large numbers with right space; weight—smaller numbers are associated with light objects and large numbers with heavier objects) should interact to influence hand movement kinematics.

Thanks to this novel method, we can assess how well numerical information is communicated through hand gestures over time. It combines the display of numbers with the performance of actions.

3. Methods

3.1 Participants

The Department of General Psychology at the University of Padua conducted this study, which involved ten participants aged between 22 and 27, averaging 23.1 (SD = 1.101). The study took place at the department's Movement Analysis Laboratory.

All participants were volunteers who signed an informed consent form authorized by the University of Padua Ethics Committee. The Edinburgh Handedness Inventory (refer to Appendix) assessed participants' manual preferences for typical activities like writing, drawing, and eating.

3.2 Stimuli

The experimental stimuli in each block were distinct and given in a predefined order. In blocks A, B, and C, three separate triplets of odd-numerical stimuli were displayed on the monitor:

- Block A:
  - Small stimulus: S1.
  - Large stimulus: S9.
  - No-go stimulus: S5.
- Block B:
  - Small stimulus: S1.
  - Large stimulus: S5.
  - No-go stimulus: S3.
- Block C:
  - Small stimulus: S5.
  - Large stimulus: S9.
  - No-go stimulus: S7.

For the final block, block D, three different letters of the alphabet were projected onto the monitor: the initial letter, A, and the last one, Z, with the letter M serving as the no-go stimulus. In addition to the experimental stimuli presented, an extra stimulus, S$, was inserted in the four blocks. This character, $, was specifically chosen for its symmetry to eliminate any indication of orientation, unlike #, which has a slight tilt to the right.

For this study, the S$ stimulus represents the baseline value. This baseline value was supplied as practice for the future motor action of kicking, thus helping the participants familiarize themselves with the task and, for comparison purposes, to determine probable changes in the temporal component of the throw between small and large stimuli and stimulus S$.

3.3 Experimental Apparatus

Participants sat on a chair before a 90 x 90 cm table and placed their right hand in the assigned starting position. The experimental setup used a green velvet surface (93.5 x 74 cm). The participant's right index finger was put into a small plastic football boot (3 cm long, 1.5 cm wide) (see Figure 1A). At the start of each trial, participants were asked to place the shoe on a footprint (3 cm long, 1.5 cm wide) painted on the velvet material. A plastic ball (2.3 cm in diameter) was placed 1cm from the footprint on a plastic ring holder (1.5 cm in diameter). Participants began by resting their right wrist on a special sponge support measuring 16 cm in length, 11 cm in width, and 6.5 cm in height. This allowed for a comfortable hand posture and a consistent kick angle for the ball. A small football goal (18 cm long, 16 cm high) was 50 cm away from the footprint.

The experimental stimuli were presented on a 24” monitor (1920 x 1080 pixels resolution, 120 Hz refresh rate) positioned at eye level with an eye-screen distance of 80 cm. The index finger and ball were marked with two reflective markers.

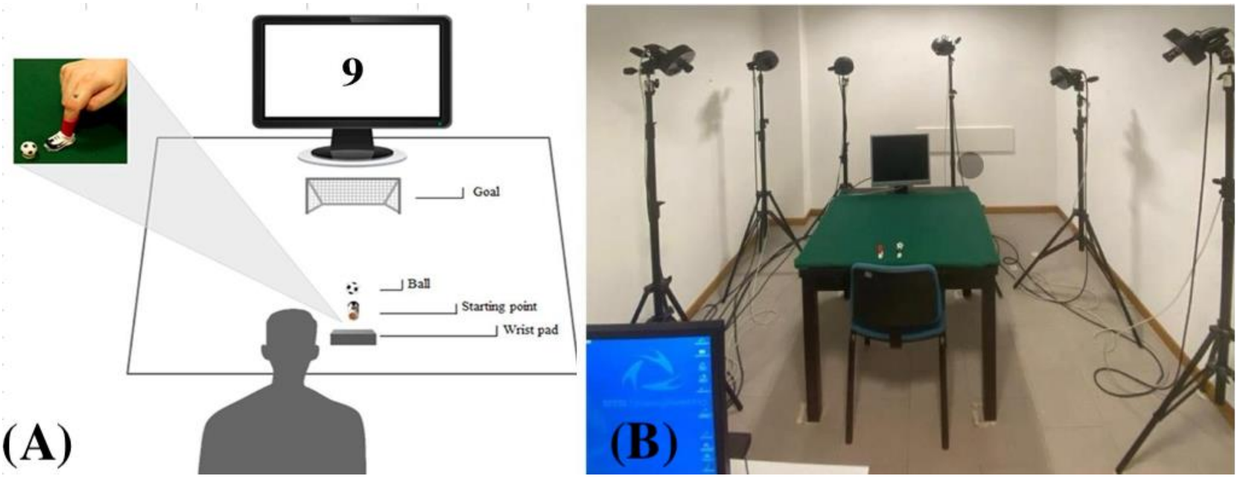


Figure 1. (A) Experimental setup. Participants were seated in front of a monitor, their index finger positioned on a footprint in front of a plastic ball and wearing a small soccer shoe. A small goal was positioned centrally regarding the participant’s position. (B) Movement Analysis Laboratory at the Department of General Psychology in Padua

3.3 Experimental Procedure

Participants underwent two sessions: a short training session as a baseline and a test phase. The instruction was to kick the ball towards the goal when the stimulus was shown. There was no guidance regarding the speed of movement. Each block included 40 trials in which the subjects kicked the ball or remained still according to the stimulus provided on the monitor, written in Arial font, black color, and size 160. For each block, there was at least one no-go stimulus to prohibit the subject from kicking the ball without considering the stimulus displayed on the monitor. Before the experimental stimulus, a black fixation cross (7.5 x 7.5 cm) was displayed on the monitor for 100 ms.

The experimenter used infrared cameras to track the subject's movement and controlled the beginning and end of acquisitions. In this experiment, the SMART DX system – a high-precision optoelectronic system with infrared cameras and a 60 Hz sampling rate (see Figure 1B) – was utilized to detect passive reflective markers, each measuring 6 mm in diameter, placed at three different locations: first, on the participant's right index finger's proximal phalanx; second, on the ball; and third, on the goal's crossbar.

The motion analysis procedure includes multiple steps, the first of which is camera calibration. This approach involves two separate parts. In the first phase, the triad representing the Cartesian system's three axes is put in the center of the workspace for static calibration. Next, a dynamic calibration is utilized to delimit the experimental space by moving the Y-axis in three dimensions within the space where the experiment would occur. Each acquisition is then rebuilt using the SMART tracker software. The obtained markers in the calibrated space will be named using a previously generated template. This enables the exact connections to be formed automatically.

3.4 Data processing and analysis

The data was analyzed in steps following the gathering of infrared camera records. The initial step was to label each marker with its proper designation according to the model (in this case, right proximal index phalanx, ball, and goal) using the SMART Tracker program. The second phase, kinematic analysis with SMART Analyzer, includes applying specialized algorithms, reviewing variable graphs for inaccuracies, and organizing the exported data into sorted files.

4. Results

The kinematic characteristics shown below were retrieved for each movement using Excel. To account for individual speed variances, the time peak was normalized concerning the movement time, the time interval between the start and the finish of the movement.

Time to Maximum Acceleration (TMA) (%) represents the proportion of movement time during which the index's trajectory achieved maximum acceleration.

Time to Maximum Trajectory Deviation (TMDev) (%) represents the movement time during which the index trajectory deviated the most from the center line.

We computed averages and relative standard deviations for each participant and kinematic index for each stimulus type.

The mean values of each parameter of interest were calculated for each participant and used in a separate repeated-measures ANOVA with the stimulus as a within-subject factor. The ANOVA was conducted with an alpha of $p < 0.05$. The means of interest were explored using main effects (post hoc t-test) and Bonferroni correction (p alpha < 0.05) to prevent type-1 errors. Statistical analyses were carried out using JASP (2023) software.

Block A – S1, S9, S$

The stimulus had a substantial effect on the normalized time of maximum acceleration (TMA) (%), as demonstrated by a repeated-measured ANOVA [$F_{(2,18)} = 15.284$; $p<0.001$; $\eta^2_p=0.629$]. Observation of S9 showed a delayed peak compared to S1 ($p=0.01$). This effect was equally significant for S1 versus S$ ($p=0.004$), (see Figure 2A).

Regarding the normalized time of maximum deviation from the trajectory to the left (TMDev– Left%), the repeated-measured ANOVA on the time at which the index's trajectory reached maximum deviation from the midline revealed a significant stimulus effect [$F_{(2,18)} = 3.657$; $p=0.046$; $\eta^2_p=0.289$]. When compared to S$, the observation of S9 resulted in a delayed peak ($p=0.035$), see Figure 2B.

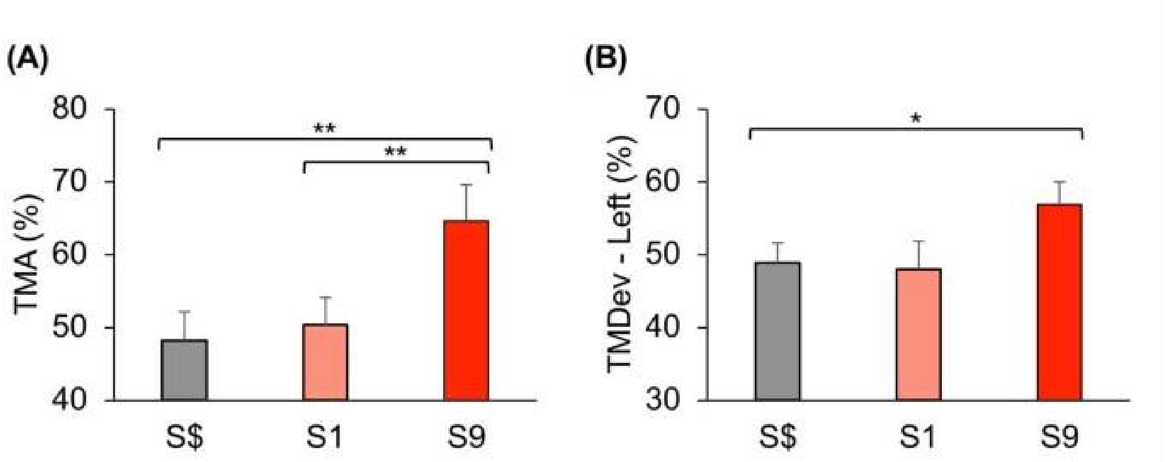


Figure 2: Graphical representation of temporal components of index movement in block A (S$, S1, S9). (A) Time to Maximum Acceleration (TMA) and (B) Time to Maximum Trajectory Deviation%). Error bars represent Standard Error. Asterisks indicate statistically significant comparisons (*=p<0.05; **= p<0.01).

Block B – S1, S5, S$

The stimulus had a substantial effect on the normalized time of maximum acceleration (TMA%), as demonstrated by a repeated-measures ANOVA [$F_{(2,18)}$ = 12.183; p<0.001; η^2_p=0.594]. S5 showed a delayed peak compared to S$ (p<0.001). This effect was similarly significant in S5 versus S1 (p=0.013) (see Figure 3).

Repeated-measures ANOVA showed no significant effect of the stimulus for the normalized time of maximum trajectory deviation to the left (TMDev-Left%).

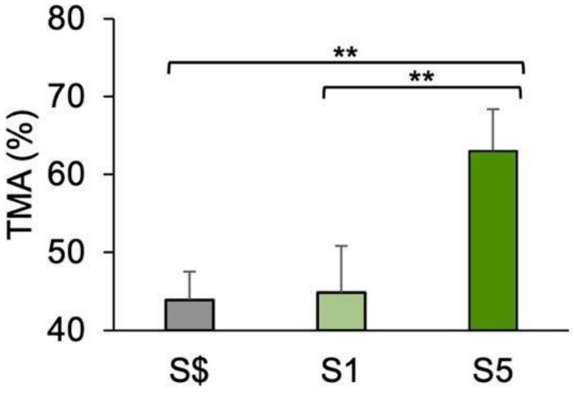


Figure 3. Graphical representation of the Normalised Maximum Acceleration time of index movement in block B (S$, S1, S5). Error bars represent Standard Error. Asterisks indicate statistically significant comparisons (**= p<0.01).

Block C – S5, S9, S$

The stimulus substantially affected the normalized time of maximum acceleration (TMA%), as demonstrated by a repeated-measures ANOVA [$F_{(2,18)} = 7.284$; p=0.005; $\eta^2_p=0.447$]. S9 showed a delayed peak compared to S$ (p=0.020)(see Figure 4).

Repeated-measures ANOVA showed no significant effect of the stimulus for the normalized time of maximum trajectory deviation to the left (TMDev-Left%).

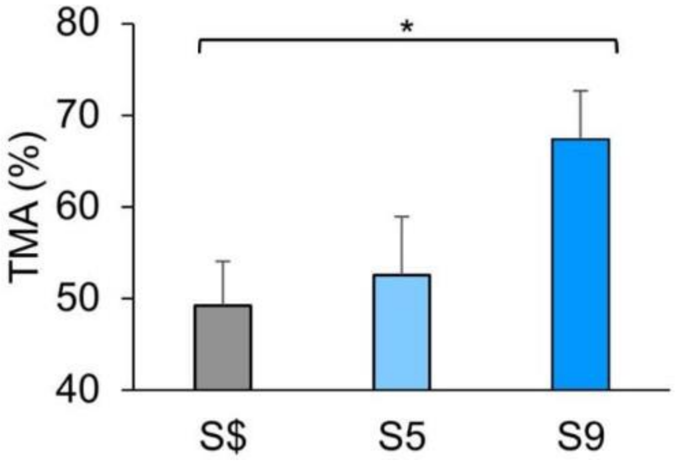


Figure 4. Graphical representation of the Normalised Maximum Acceleration time of index movement in block C (S$, S5, S9). Error bars represent Standard Error. Asterisks indicate statistically significant comparisons (*= p<0.05).

Block D – SA, SA, S$

The stimulus substantially affected the normalized time of maximum acceleration (TMA%), as demonstrated by a repeated-measures ANOVA [$F_{(2,18)} = 9.286$; p=0.002; $\eta^2_p=0.508$]. SZ showed a delayed peak compared to S$ (p=0.009)(see Figure 5).

Repeated-measures ANOVA showed no significant effect of the stimulus for the normalized time of maximum trajectory deviation to the left (TMDev-Left%).

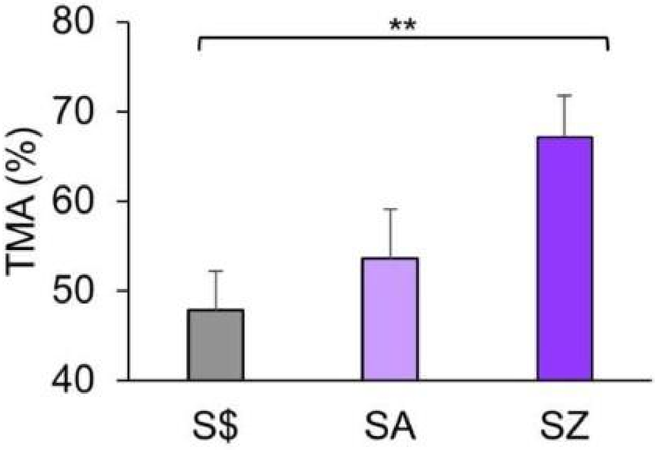


Figure 5. Graphical representation of the Normalised Maximum Acceleration time of index movement in block D (S$, SA, SZ). Error bars represent Standard Error. Asterisks indicate statistically significant comparisons (**= p<0.01).

5. Discussion

This study aimed to see if numerical processing altered the performance of reaching actions. Participants were instructed to kick the ball after viewing a large or small numerical stimulus or two letters of the alphabet. Our key finding is that, despite the actions being identical, a delayed peak in the period of maximum acceleration was found following the presentation of the large number stimulus, as opposed to the neutral stimulus $. Regarding the maximum deviation of the trajectory to the left, only block A showed a delayed peak of the big number recorder concerning the neutral stimulus $.

The spatial and temporal features of finger motion in reaction to numbers can also be explained using embodied number representation theory. This viewpoint argues that numbers are embodied in bodily experiences rather than abstract things. Our cognition can be influenced by how our bodies move (Wilson, 2002; Barsalou, 2008; Patro et al., 2015). For example, during learning, sense-motor activation changes the newly acquired representation (Fischer & Zwaan, 2008; Fischer, 2012). Thus, the theoretical perspective of embodied numerical cognition provides an interesting new approach to studying mathematical skills. This paradigm does not require specific skills and may be performed by pre-schoolers. As a result, this model that uses finger trajectories to assess mental calculations can be used as a diagnostic tool to examine mathematical skills development in healthy and pathological subjects (Booth & Siegler, 2006; Rugani et al., 2018).

Rugani and colleagues' 2018 study examined the kinematics and direction of calcium choice when given two types of stimuli: symbolic numbers (S2, S8) and non-symbolic numbers (groups of 2 and 8 items). Participants had to kick the ball and had two goals in which they could shoot. The results showed that the production of the ball kick to the left increased when the symbolic small number stimulus was presented. However, this did not occur when the non-symbolic small stimulus was presented. As a result, the spatial representation of numerical scale influences the subject's motor reaction.

Moreover, kinematic analysis demonstrated that both small and larger numerical stimuli influenced the time of motor execution. According to Rugani et al., 2018, participants took longer to plan the action but finished the shoot quicker in response to a few stimuli. Thereby, numerical information affects how the body moves. For example, we saw a delayed acceleration peak when large numerical stimuli were shown as opposed to baseline stimuli.

Prior studies (Weir et al., 1991; Brouwer et al., 2006; Eastough & Edwards, 2007) have examined the connection between reaching and grasping action and object properties (such as weight). According to these studies, adjustments are made to pre-contact kinematics to improve object gripping.

The speed and acceleration of an object have been seen to increase in proportion to its weight. Accordingly, if the object to be lifted is heavy, both acceleration and velocity will rise (Ansuini et al., 2016).

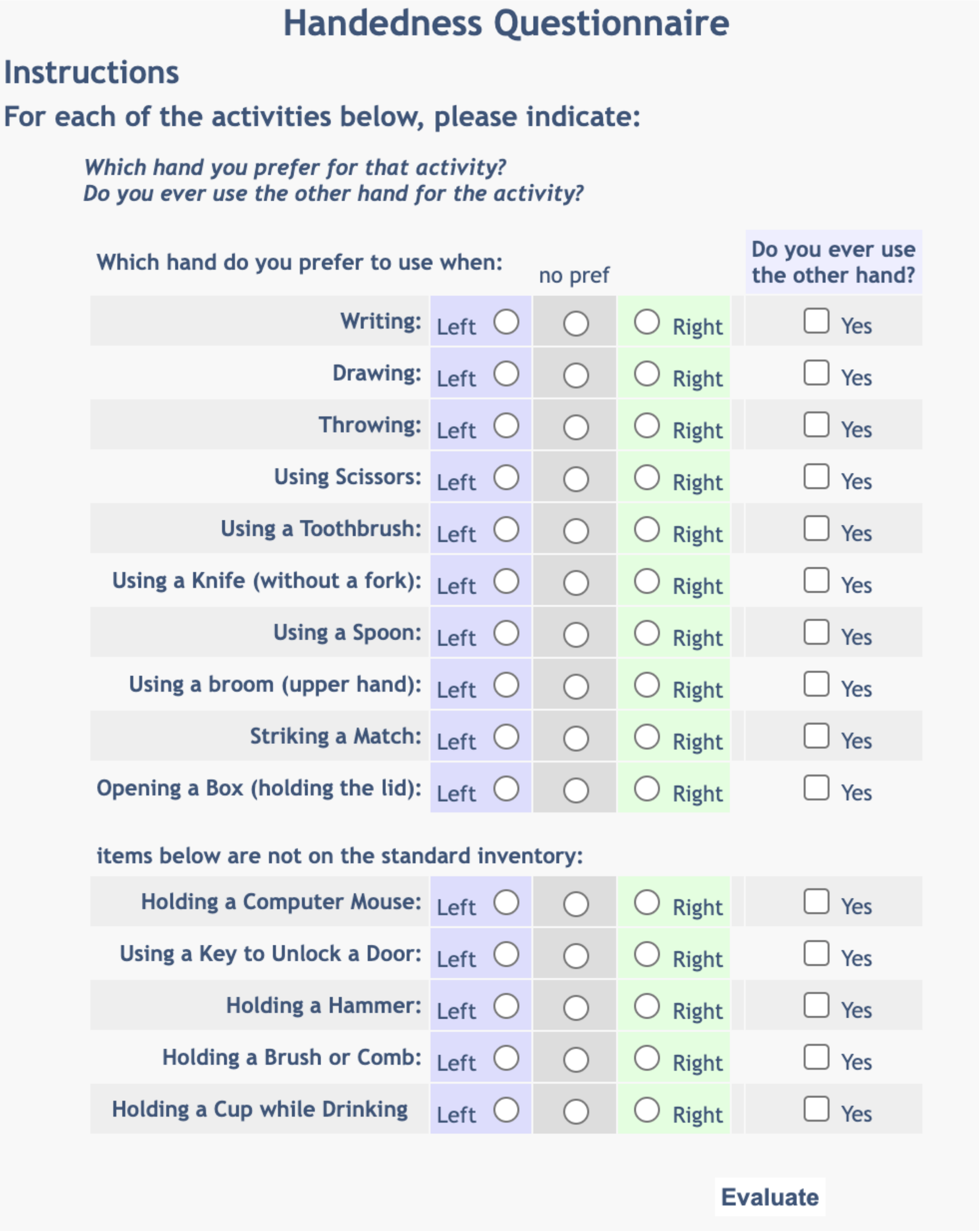
When observing the temporal component of the movement, an anticipated peak of acceleration is usually an indication of perturbation: the motor system compensates for unforeseen events by anticipating the peak of acceleration to lengthen the final phases of the action, adjust the gesture, and thus prevent the movement's duration from being prolonged (Castiello et al., 1993, 1998). The acceleration peak is postponed when the movement is optimized and free of criticalities.

6. Conclusion

This study analyzes the relationship between the spatial number line and action execution. Research suggests that spatial number association may have evolved throughout time (de Hevia & Spelke, 2009; de Hevia et al., 2012; McCrink & Opfer, 2014; Nuerk et al., 2015; Rugani & de Hevia, 2016; Möhring et al., 2017). Furthermore, it could shed light on whether and how symbolic and non-symbolic numbers affect the sensorimotor transformations involved in hand motor control. The relationship between finger counting and motor control of the hand in number processing (Di Luca et al., 2006; Fischer, 2008; Sixtus et al., 2017) is another aspect of this study that is especially pertinent. This relationship persists in adults and suggests a connection between numbers and motor actions of the hand (Hatano et al., 1977; Hubbard et al., 2005).

The investigation of numerical cognition and its spatial link would also be made possible by this study, which is based on an engaging and self-motivating task without fear accompanying youngsters learning mathematics. Individuals who present extreme anxiety when it comes to mathematics often avoid it, which lowers their chances of improving their abilities and competencies (Ashcraft, 2002). Therefore, before and during mathematics teaching, this paradigm could be utilized to research numerical processing and motorization in development. Motion kinematics could provide a novel means of identifying possible mathematical deficiencies and a precise indicator of spatial-numerical relationships.

7. Appendix



Handedness Questionnaire

Instructions

For each of the activities below, please indicate:

Which hand you prefer for that activity?
Do you ever use the other hand for the activity?

Which hand do you prefer to use when:		no pref		Do you ever use the other hand?
Writing:	Left ○	○	○ Right	☐ Yes
Drawing:	Left ○	○	○ Right	☐ Yes
Throwing:	Left ○	○	○ Right	☐ Yes
Using Scissors:	Left ○	○	○ Right	☐ Yes
Using a Toothbrush:	Left ○	○	○ Right	☐ Yes
Using a Knife (without a fork):	Left ○	○	○ Right	☐ Yes
Using a Spoon:	Left ○	○	○ Right	☐ Yes
Using a broom (upper hand):	Left ○	○	○ Right	☐ Yes
Striking a Match:	Left ○	○	○ Right	☐ Yes
Opening a Box (holding the lid):	Left ○	○	○ Right	☐ Yes

items below are not on the standard inventory:

Holding a Computer Mouse:	Left ○	○	○ Right	☐ Yes
Using a Key to Unlock a Door:	Left ○	○	○ Right	☐ Yes
Holding a Hammer:	Left ○	○	○ Right	☐ Yes
Holding a Brush or Comb:	Left ○	○	○ Right	☐ Yes
Holding a Cup while Drinking	Left ○	○	○ Right	☐ Yes

Evaluate

Edinburgh Handedness Inventory, subjects entered their manual preferences in this form.

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