



**UNIVERSITÀ DEGLI STUDI DI PADOVA**

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**Elaborato finale**

**Influence of grasping and pointing on  
the numerical distance effect**

*Relatrice*

**Prof.ssa** Mariagrazia Ranzini

*Correlatore esterna*

**Dott.ssa** Maria Silvia Saccani

*Laureando:*

*Jacopo*

*Freddi*

*Matricola:*

*2074187*

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## **Abstract**

Numbers play a major role in our life, whether it is for paying the bill or knowing how many dishes you need for today's dinner. As kids, we engage with numbers first using our hands; as adults, we might still use them to help us count. The work presented here follows a recent experiment (Ranzini et al., 2022a) to investigate the influence that hand actions have on our processing of numbers. In particular, this study focuses on the influence of grasping and pointing actions on a number comparison task. The experimental tasks consisted in performing a grasping, pointing or squeezing (control condition) repeatedly, followed by a number comparison task, with stimuli going from 1 to 5. Expected results were to find an increased numerical distance effect in trials that followed grasping actions and a decreased effect in trials that followed a pointing action. Although these hypotheses were not confirmed, secondary analyses found that tasks that followed a grasping action were the fastest overall, and that the participants mean reaction time showed strong correlations with some tests of the neuropsychological assessment, such as fine motor skills tests and approximate calculus tests. The common neural substrates underlining number comparison and grasping could explain both the fast reaction times after grasping and the correlation with fine motor skills. The correlations with the approximate calculus test support the view of the ANS as a common system for number comparison and numerical approximation.

## **1. Introduction**

Hands play a key role in our representation of numbers. Most cultures use fingers to count, often associating a digit to a specific finger. For instance, Western cultures use to associate "one" with the thumb (Lindemann et al., 2011), and some cultures even use all parts of their body to represent numbers (Wassmann & Dasen, 1994). Studies have also shown that finger gnosis, i.e., the ability to represent and discriminate one's fingers, is a predictor of future numerical skills in children (Noël, 2005).

In neuropsychology, lesions in the left posterior parietal lobe can cause both finger agnosia and acalculia, together with agraphia and right-left disorientation (Ardila, 2020), a condition known as the Gerstmann syndrome. The Gerstmann syndrome has been often taken as evidence of digit-number association, albeit it is worth noting that the origin of

the syndrome is still controversial. The connection between hands and numbers is also observed by neuroimaging studies: areas involved in the representation of fingers are also active during mental arithmetic tasks (Andres et al., 2012). Moreover, number processing areas show great overlap with areas involved in grasping and reaching (Ranzini et al., 2022b).

In this work, I present a study aimed at extending current knowledge regarding the connection between numbers and the hand actions of grasping and pointing. This work is divided in the following sections: theoretical framework, methods, results, discussion and conclusion.

## **2. Theoretical framework**

### *2.1 The Triple Code Model*

Numerical cognition is a field of experimental psychology that investigates how numbers are processed, represented and manipulated, and its classic theory is the *Triple Code Model* (TCM; Dehaene, 1992; Dehaene & Cohen, 1997). The TCM states that numerical information is represented in three ways or codes: a visual symbolic representation, called the visual Arabic number form (e.g.: “3”); an auditory and written representation which is not specific to numbers, called the auditory verbal word frame (e.g. “three”); and an analogue magnitude representation.

Each code enables different numerical abilities. The visual Arabic number form enables complex calculations and parity judgments, abilities acquired through the development of a dedicated positional system that allows the use of arithmetical algorithms. The auditory verbal word frame feeds on the general linguistic system and allows verbal counting (e.g.: “one, two, three...”) and arithmetical fact retrieval (e.g.: “two times two is four”), as these abilities are considered to be no different from other automatic series (e.g.: naming the letters of the alphabet or the names of the months). In TCM’s view, the development of these abilities is supported by the more general abilities of quantity approximation and comparison, which are enabled by the analogue magnitude representation. This is the only semantic representation of numbers (how big something is, approximatively and compared to others), thus giving meaning to the

symbolic representation of the other codes. This system is also known as the Approximate Number System (ANS) and is thought to be innate, as approximation and comparison abilities can be observed in pre-verbal children as well as animals (Dehaene et al., 1998; Izard et al., 2009).

## 2.2 Embodied cognition

Embodied cognition theories suggest that sensorimotor features, such as the use of fingers to count, have a role in the acquisition of knowledge and its mental representation. Differing from the grounded aspects of cognition, which refer to those constraints imposed by the physical world (e.g., gravity), embodied cognition (also referred to as “embodiedness”) indicates the cognitive aspects that reflect the sensorimotor constraints posed by the body (Fischer, 2012). While the first ones are expected to be universal, the latter are thought to be culturally-specific.

An experimental example of embodiedness in the numerical field is the Spatial-Numerical Association of Response Codes (SNARC) effect: in Western participants, studies show that small numbers are associated with a faster left-side response and large numbers are associated with a faster right-side response (Dehaene et al., 1993; Wood et al., 2008). This likely reflects the habit in Western cultures to write from left to right, causing the *Mental Number Line* (MNL) to present smaller numbers on the left and larger ones on the right<sup>1</sup>.

Since the hypothesis that cognition takes its roots in perception and action, many authors proposed this could happen in different ways. Meteyard et al. (2012) distinguished between strong, weak and secondary embodiment. Strong embodied theories state that meaning is derived from a “full simulation”: during semantic tasks primary motor and sensory cortices are expected to be active, thus recreating the sensorimotor experience occurred during knowledge acquisition, to convey meaning. Weak embodiment states only a partial dependency on motor and sensory systems, predicting an activation in anterior or adjacent areas but not on the primary sensory and motor areas themselves. Lastly, secondary embodiment proposes no hard bound between semantics and sensorimotor content, still maintaining the idea of an association between the two.

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<sup>1</sup> Recent evidence from animal studies suggests that the SNARC effect might also have a biological component, but the matter is still controversial (See Rugani et al., 2015; Giurfa et al., 2022; Pitt et al., 2023; for this issue).

Meteyard ends stating that neuroimaging data, while supporting embodied theories, does not support strong embodiment.

Regarding numerical information, various studies document its representation in the sensorimotor cortices. In a recent work, Sixtus et al. (2023) divided the general numerical concept in three more specific ones: ordinality, cardinality and magnitude, and suggested that these are grounded in the sensorimotor system in different ways, admitting some redundancy. In his view, ordinality is grounded through spatial and temporal maps acquired through learning, as the MNL (i.e.: the numerical sequence is ordered on a spatial axis determined by culture, going from left-small to right-big in Western cultures). At the neural level, ordinality is grounded in areas representing spatial aspects (superior parietal lobes and precuneus) and memory-related areas, such as the entorhinal and prefrontal cortices.

Cardinality is grounded in the first place through the innate Parallel Individuation (PI) system (also referred to as Object Tracking System) which enables subitizing: the ability to almost immediately represent the cardinality of groups of 3-4 items (Piazza, 2010). The PI system is subject to maturation and is a prerequisite to the grounding of bigger cardinalities, which are grounded through learnt processes such as counting. Cardinality is an exact measure, and it differs from magnitude which is approximate. Magnitude reflects the Approximate Number System (ANS), which is an innate numerical ability granting the ability to estimate the numerosity of a set of items. It is grounded through the Generalized Magnitude System (GMS), which I will focus on for the sake of this work.

### *2.3 A Theory Of Magnitude*

The GMS was first postulated by A Theory Of Magnitude (ATOM), which argues that prothetic dimensions, meaning dimensions that can be experience as “more than/less than”, such as time, space and quantity (and possibly other magnitude, like brightness) share a common elaboration system (Buetti & Walsh, 2009; Walsh, 2003). A recent meta-analysis of neuroimaging studies by Cona et al. (2021) supports this theory, but also suggests that the areas that elaborate different types of magnitudes present a gradient, thus renaming the theory “GradiATOM”. Focusing on space and time, this meta-analysis found a system of commonly recruited areas, including: the supplementary motor area

(SMA), pre-SMA, the right inferior frontal gyrus (IFG), the intra-parietal sulci (IPS), the frontal operculum and the left precentral gyrus (PCG). Notably, the SMA presents an anterior-posterior gradient, with the anterior region (i.e., pre-SMA) activating more for space and the posterior for time. A dorsal-ventral gradient was found for parietal and frontal regions, with time recruiting ventral regions and space recruiting dorsal regions.

#### *2.4 Common neural substrates*

If different magnitudes, including numerical magnitude, share common neural substrates, so do numbers and hand actions. In a recent meta-analysis Ranzini et al. (2022b) investigated these common substrates. Regarding number processing, areas of great interest are: the left angular gyrus (AG), the posterior parietal lobes (PSPL), the horizontal segment of the intraparietal sulcus (hIPS), the frontal gyrus (FG) and the prefrontal cortex (PFC). While most of these areas are not number-specific and are also involved in other processes, such as visuo-spatial attention (PSPL) and linguistics (AG), the numerical cognition field took particular interest in the IPS, which is crucial in symbolic and non-symbolic number processing and is part of the magnitude network. Importantly, the IPS, together with the posterior and superior parietal lobe, is also involved in the grasping network.

Symbolic number comparison finds its main clusters of activation in the inferior parietal lobe (IPL), left PCG, SMA, and right IFG. Clusters also extend to the SPL, corpus callosum, AG, postcentral gyrus (PoG), supra-marginal gyrus (SMG), rolandic operculum, insula, middle frontal gyrus (MFG), superior temporal gyrus (STG), middle cingulate cortex, superior frontal gyrus (SFG) and frontal inferior longitudinal fasciculum. Regarding the reaching and grasping network, the main clusters are located in the PCG, cerebellum, corpus callosum, SPL, IPL, SMA, insula and precuneus. As we can see, the two networks share common neural substrates, with great overlap in the bilateral IPL, left PCG and SMA, and smaller overlaps in the SMG, PoG, left PCG, rolandic operculum, IFG, insula, middle cingulate and paracingulate gyrus.

Focusing only on hand grasping, clusters are found in the cerebellum, left PCG, SMA, rolandic operculum, putamen, left PoG, IPL and SMG. The grasping and symbolic number comparison networks overlap in the IPL, SPL and PoG. This meta-analytical work showed that the symbolic number comparison network is mostly integrated in the one for reaching and grasping, supporting an embodied approach to numerical cognition.

It is also worth noting that these common neural substrates are in line with the ATOM theory: areas elaborating concrete magnitude, implied for reaching and grasping, seem to also elaborate symbolic (numerical) magnitude.

### *2.5 Grasping and number comparison*

According to TCM, number comparison is supported by the ANS (Dehaene, 1992). The ANS is a noisy system: numbers are represented in an approximate and compressed way. Thus, two sets of objects can only be discriminated if they differ by a given ratio, following Weber's law (Piazza, 2010). The noise of the system also increases as numbers get larger. That is, larger numbers have a more approximate representation. This view is supported by two ratio-based effects: the size effect and the distance effect. These effects were first described by Moyer and Landauer (1967). When participants were asked to respond which of two digits was the larger, they observed that:

- a) reaction times (RTs) were slower with larger numbers (size effect);
- b) RTs were slower with a smaller numerical distance between the digits (distance effect).

Much like in perceptual tasks, such as brightness and loudness comparison, in number comparison the size and distance effects follow Weber's law. Moyer's evidence suggests that the symbolic number format (e.g.: "3") is converted in an analogue magnitude representation (the ANS), thus permitting a comparison that happens much like the one between physical stimuli (Dehaene et al., 1990). This is in line with the TCM. Moreover, a ratio-based performance can be observed in pre-verbal children and animals in non-symbolic number comparison tasks, thus suggesting that the ANS is innate and not human-specific (Dehaene et al., 1998). Although it has been widely accepted that symbolic and non-symbolic number comparison are both elaborated by the ANS, this concept has been recently challenged (see Krajcsi et al., 2016; 2018).

From a neural point of view, the number comparison network and the grasping/reaching network have a lot in common (Ranzini et al., 2022b). In fact, several studies show that numerical magnitude and grasping influence each other. Small numbers facilitate precision grip, while large ones facilitate power grip (Lindemann et al., 2007; Moretto & Di Pellegrino, 2008). Moreover, in the early stages of a reach to grasp, action grip aperture is influenced by the number printed on the object that is to grasp, with larger numbers causing a larger aperture (Andres et al., 2008). Namdar et al. (2014) confirm these results

and suggest that the influence of numerical magnitude on grip aperture happens in an automatic manner.

Concerning the influence of grasping, it has been observed that learned grasping associations causes an interference effect in numerical magnitude processing (Badets & Pesenti, 2010; 2011). Badets et al. (2012) also show that observed grip closure and grip opening bias random number production: participants were more likely to produce smaller numbers when observing grip closure, and larger ones when observing grip opening. These results are in line with ATOM, which suggests that numerical magnitude and physical magnitude (grip aperture) share a common elaboration system.

### *2.6 Influence of pointing*

The work presented here stems from a previous experiment, in which Ranzini et al. (2022a) investigated the influence of grasping and pointing on the processing of numerical magnitude. Their study showed that RTs were slower when performing a number comparison task after repeated pointing. Moreover, for small numbers only ( $< 5$ ), the distance effect seemed increased after performing grasping actions, and decreased after pointing.

In their work, Ranzini et al. (2022a) used a motor adaptation paradigm, which was also used in the study presented here. Differing from previous association studies on grasping and number processing, hand actions and number comparison tasks were temporally dissociated: participants performed the hand actions first, and then the number comparison task. The assumption is that the progressive repetition of a motor tasks, i.e., motor adaptation, causes neural adaptation: the neural activity of the brain areas involved progressively decreases (Grill-Spector, 2006). Motor adaptation would explain these results, since grasping shares common neural substrates with number comparison, while pointing does not. Thus, the increase in the numerical distance effect after grasping and the decrease after pointing.

The aim of this study is to assess the influence of the hand actions of grasping and pointing on the processing of numerical magnitude, elaborating on the results of Ranzini et al. (2022a).

We expect to observe:

- 1) an increased numerical distance effect in number comparison tasks performed after grasping actions;
- 2) a decreased numerical distance effect after pointing actions.

### **3. Method**

#### *3.1 Participants*

We tested 40 participants, 6 of which were excluded during the data analysis because of incompatibilities with the experimental protocol or errors occurred during the experimental phase, such as malfunctions of the software used for the experiment. All participants were right-handed, had a normal or corrected to normal vision, had no history of photosensitivity or neuropsychological disorders, no history of dyscalculia or acalculia, and did not take any medical drugs that could induce anxiety, cognitive fatigue or photosensitive reactions. Handedness was assessed using self-report and the Edinburgh Handedness Inventory scale (Oldfield, 1971).

The final sample consisted of 34 Italian-speaking healthy adults (mean age = 21.8, SD = 1.6, females = 19), with a schooling age between 13 and 19 (mean = 16.1, SD = 1.4). Participants were recruited by advertising and word of mouth, and received a compensation of 25€ for participating in the experiment.

Prior the beginning of the experimental session, each participant read and signed a written informed consent.

#### *3.2 Neuropsychological assessment*

Before the experimental phase, every participant underwent a neuropsychological assessment, consisting in a series of tests.

The tests followed this order:

- a) Montreal Cognitive Assessment (MoCA): it consists of several short tasks presented on a single A4 paper sheet, and it is administered in no longer than 10 minutes. The test assesses several cognitive domains. All participants had a scoring  $\geq 26$ , which is considered normal (Hobson, 2015; Santangelo et al., 2015).
- b) Finger Gnosia test: since finger recognition and discrimination are shown to be reliable predictor of numerical skills (Noël, 2005), we tested these two abilities to

assess no clear finger agnosia in our participants. The test is subdivided in two main tasks: the first one consists in a single or double finger recognition with contemporary touches. This task had 15 trials for each hand. The second task consisted in a strictly double finger recognition with consecutive touches. Participants also had to name the fingers in the order they were touched. This task had 5 trials for each hand. The test had a maximum score of 40 ( $15 * 2 + 5 * 2$ ) (Benton, 1955)<sup>2</sup>.

- c) Digit Span Forward: this test is used to assess verbal short-term memory. More specifically, given the forward quality of the test, it was used to assess verbal working memory (Monaco et al., 2013). Subjects were presented with a sequence of digits, increasing by one with every trial. The sequences were listed vocally by the experimenter, and participants were asked to retrieve the entirety of the list right after, in the same order.
- d) Corsi Span Forward: similar to the digit span forward, the Corsi test is used to assess visuo-spatial working memory. Participants were presented with a wooden board containing nine blocks on top of it, and were asked to retrieve a sequence of block positions indicated by the experimenter, in order. The sequence length increased by one with every two out of three correct trials.
- e) LSC-SUA: only the calculation area of the LSC-SUA battery was used. This is divided in: number dictation (20 trials), number reading (20 trials), mental calculation (10 trials), arithmetical facts (30 trials), approximative calculus (16 trials) and transcription of numbers to digits (10 trials) (Montesano et al., 2020). One point was given for each correct trial.
- f) Purdue Pegboard Test: the test is used to assess manual dexterity, specifically fine motor skills. It consists of a rectangular board presenting two parallel lines of 25 holes each spacing 1 cm apart running along the entirety of the board. The board also presents four holders containing pegs for the left hand, pegs for the right hand, collars and washers. Subjects must place as many pegs in the holes as possible in 30 seconds, first with the right hand, then with the left, and then with both hands at once. This is followed by an assembly task, where they must assemble as many

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<sup>2</sup> Differing from Benton, we did not take in account the initial identification of each finger for the scoring, resulting in a total score of 40 instead of 50.

pegs, collars, and washers as possible in one minute (Tiffin & Asher, 1948; Lawson, 2019).

- g) 9-Hole Peg Test (9-HPT): as the previous one, this test was also used to assess manual dexterity. The 9-HPT consists in a rectangular board presenting a holder containing pegs and a square of nine holes. Participants must insert all pegs in the holes and then take them out. The scoring is equal to the total time to complete the action (Mathiowetz et al., 1985; Wang et al., 2015). The task was first performed with the right hand, which was the dominant, and then with the left.

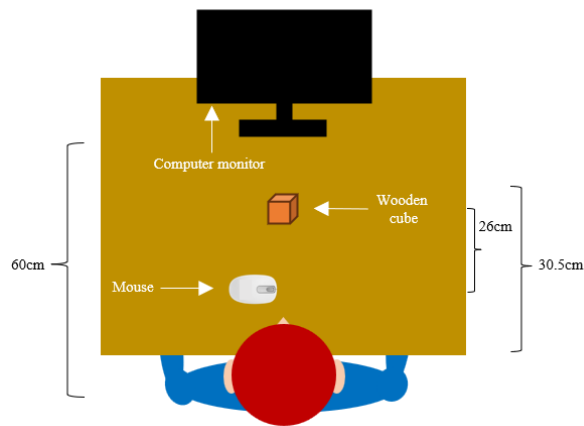
The neuropsychological assessment lasted about one hour. Participants scorings with the relative standards can be found in **Table 1**. The assessment took place in the General Psychology Department of the University of Padua (DPG, Università degli Studi di Padova). Participants took part in the experiment within 10 days after this phase. Due to a malfunction of the fNIRS equipment, the experimental phase of one participant was delayed and took place one month after the neuropsychological assessment.

	Mean Scoring	SD
MoCA	28.6/30	1.1
Finger Gnosia	38.1/40	1.7
Digit Span Forward	6.6	0.9
Corsi Span Forward	6.1	1.0
LSC-SUA: dictation	18.0/20	2.9
LSC-SUA: reading	19.8/20	0.4
LSC-SUA: mental calculation	6.7/10	2.6
LSC-SUA: arithmetical facts	23.9/30	4.2
LSC-SUA: approximative calculus	9.7/16	2.8
LSC-SUA: transcription	9.0/10	1.5
Pegboard: right hand	12.9	1.8
Pegboard: left hand	12.5	1.7
Pegboard: both hands	10.1	1.3
Pegboard: assembly	35.6	3.9
9-Hole Peg Test	17.56s	2.13

**Table 1** Mean scoring and standard deviation is reported. Note that a higher scoring corresponds to a higher performance for all tests, except for the 9-Hole Peg Test: in this test the scoring is noted in seconds; a higher score corresponds to a worse performance.

### 3.3 *Experimental setting*

Participants were sat on a table with a screen positioned at approximately 60 cm from them. They were presented with a wooden cube of 2 mm<sup>3</sup> positioned at a distance of 30.5 cm, and a mouse positioned sideways (pointing to the right) at 26 cm from the wooden cube and approximately 4.5 cm from the participants. Both the cube and the mouse were fixed to the table. The measures relative to the mouse were taken using the centre of the mouse as the reference point. **Figure 1** illustrates the experimental setting. Participants were asked to keep their hands facing downwards on their legs and to take out the right hand only when required.



**Figure 1** Illustration of the experimental setting.

### 3.4 Materials and Procedure

The experiment consisted in a within-subjects design with three factors: Action Type (squeezing, grasping, pointing), Number Magnitude (small = 1, 2; big = 4, 5) and Number Distance (close to the reference = 2, 4; far from the reference = 1, 5). The experimental session consisted in two sequences of three blocks, both repeating 5 times. The blocks were named Squeezing, Grasping and Pointing, after the action task included in each of them. The order of block presentation was randomized between participants, as illustrated in **Table 2**. Every block consisted in an action task (squeezing, grasping or pointing), followed by a number comparison task.

In the squeezing task, participants were presented with a fixation point lasting 5000 ms. During this time, they were instructed to do a squeezing action with the fingers of their right hand, palm facing upwards. The motion was illustrated by the experimenter. In the Grasping and Pointing tasks participants were asked to start from a pinching position on the left button of the mouse and to perform either a grasping or a pointing action on the cube positioned in front of them. Instructions indicated to grasp the cube using the thumb and the index finger for the Grasping task, and to touch the centre of the cube with the index finger for the Pointing task.

After every grasping/pointing, the participants had to return to the starting position and click the left mouse button. After they did so, a beep sound informed them to repeat the action. This procedure was repeated 4 times. During these tasks, participants were presented with a black screen that acted as a visual cue that the action task was on. These action tasks are illustrated in **Figure 2**. Then, a long beeping sound informed them that

the number comparison task was about to start. In this task, participants were presented with an initial fixation point lasting 250 ms. This was followed by a numerical digit presented in the centre of the screen. The digit could be either 1, 2, 4 or 5 (the target numbers). Participants had to judge whether the number on the screen was smaller or bigger than 3 (the reference number). They were asked to respond verbally as fast as possible. The verbal responses could be either “Ma” or “Mi”<sup>3</sup>, depending on the target number being respectively bigger or smaller than the reference. The target number lasted on the screen until response (time limit = 3000 ms), and was followed by another digit immediately after, for a total of four times. The total duration of the number comparison task was no longer than 4 seconds. To increase the sensibility of the microphone to the RTs participants accuracy was noted manually by the experimenter, and the microphone only recorded the RTs. Each participant did a total of 120 number comparison trials (3 action \* 4 numbers \* 5 repetitions \* 2 sequences). The four number stimuli (1, 2, 4, 5) were presented in a random order. The experiment was built in OpenSesame (version 4.0.24). Generic instructions appeared at the beginning of every sequence, and specific instructions appeared before each block. In addition, instructions were also given verbally by the experimenter. Before the experimental trial, participants performed a short training which consisted in a single sequence of squeezing block – grasping block – pointing block.

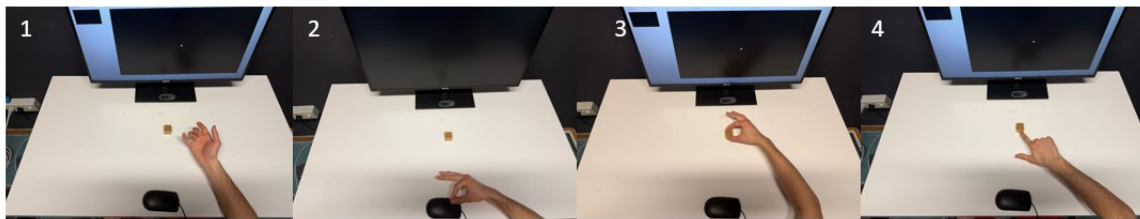
After the training, participants also performed a baseline run which consisted in just the number comparison task, repeated 5 times. The baseline run was also performed after the experimental trial. In the “Results” section, these two runs will be referred as “baseline”. The timeline of the experiment is illustrated in **Figure 3**.

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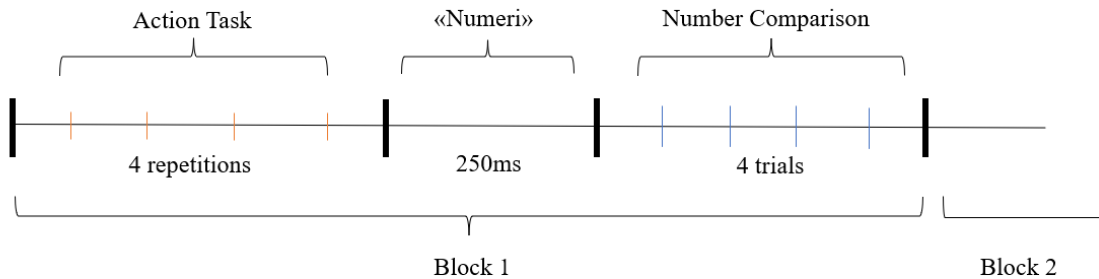
<sup>3</sup> “Ma” and “Mi” correspond to the “Maggiore” and “Minore”, translating to “bigger” and “smaller” in italian.

Order	Sequence 1			Sequence 2		
	1	2	3	1	2	3
Participant 1	Squeeze	Grasping	Pointing	Squeeze	Pointing	Grasping
Participant 2	Squeeze	Pointing	Grasping	Squeeze	Grasping	Pointing
Participant 3	Grasping	Pointing	Squeeze	Pointing	Grasping	Squeeze
Participant 4	Pointing	Grasping	Squeeze	Grasping	Pointing	Squeeze
etc...						

**Table 2** The table illustrates the between-subject randomization of the experimental blocks. Each participant performed two subsequent sequences, as indicated in the table.



**Figure 2.** The squeezing action (1), the starting position (2) and the actions of grasping (3) and pointing (4).



**Figure 3.** The timeline of the experiment. The script “Numeri” (i.e., “Numbers”) informed the participant that the number comparison task was about to start.

### 3.5 fNIRS Recording and Resting State

During the experiment we traced the brain activity of our participants using functional Near Infra-Red Spectroscopy (fNIRS). fNIRS is a neuroimaging technique that measures the Blood-Oxygenated Level Dependent signal (BOLD): the changes in concentration of oxygenated and deoxygenated hemoglobin in brain tissue occurring after a certain stimulation. It is an optical technique, as it uses infra-red light to detect the concentration

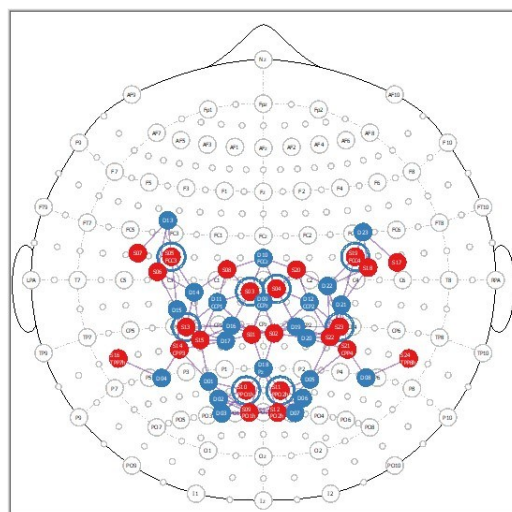
of hemoglobin (Pinti et al., 2020). This is an indirect measurement of the brain activity, as a higher oxygenation level is used to infer higher activation of a specific area.

For the montage, we used 47 optodotes, divided in 24 sources and 23 detectors. In addition, we used 8 short channels: these are detectors placed directly under a source to create a short channel.

The optodotes were placed according to a cerebral map, constructed using the MNI coordinates found in literature that correspond to the brain areas of major interest for our research (Andres et al., 2012; Berteletti & Booth, 2015; Soylu & Newman, 2016; Soylu, 2017; Arsalidou et al., 2018; Vogel & Smedt, 2021; Sixtus et al., 2023). The montage is illustrated in **Figure 4**.

We recorded the brain activity during the entirety of the experiment, including the initial and final baseline runs (but excluding the practice run). We also recorded the resting state activity of our participants to disentangle the intrinsic brain activity from the stimuli-induced activity (Northoff et al., 2010). The resting state (or resting awake state) is defined as the baseline activity of the brain when it is not perturbed by any kind of outer stimuli while maintaining a state of consciousness (Shulman et al., 2009). The recording of the resting state activity was done first, before all other phases. It lasted 15 minutes, during which participants were instructed to stay as still as possible, with their eyes open. They were presented with a fixation point where they could redirect their sight to prevent it from wandering.

The results of the fNIRS recording will not be discussed here.



**Figure 4.** This map shows the positioning of the optodes for the fNIRS recording. Red dots indicate the sources, blue dots indicate the detectors. Circled in blue are the sources with short channels under them.

## 4. Results

### 4.1 Main analysis

In this work, I only considered the behavioural results. Out of the 40 participants who were tested, 34 were taken in consideration for the data analysis. Six participants were excluded from the analysis due to incompatibilities with the experimental protocol or software malfunctions occurred during the experiment. The data analysis was run in R Studio (R version 4.3.1) and JASP (version 0.19.3.0). For statistical relevance, we consider  $\alpha = 0.05$ .

The data from all the participants was merged into a single database. This database consisted in the RTs for every number comparison trial, divided by subject, type of action and distance. The two main factors analysed were “action type” (levels: “baseline”, referring to the baseline trials; “grasping”; “pointing”; “squeezing”) and “distance” (levels: “far”; “close”). The factor “action type” referred to the action performed before the relative number comparison task. The factor “distance” referred to the numerical distance between the stimulus and the reference number (3), with “far” referring to stimuli “1” and “5” and “close” referring to “2” and “4”. From this database, I removed trials where the microphone did not pick up the participants response, and trials with incorrect response (2.09%). In order to exclude outliers, I calculated the cutoff for each participant. The cutoff was determined by the formula: mean + standard deviation \* 2.5. The mean and standard deviation were relative to each participant’s RTs. RTs over their relative cutoff were excluded (2.13%). There were no RTs under 250 ms. After the data cleaning, 5173 number comparison trials were available for the analysis.

A series of t-tests were run in R Studio to compare the reaction times of the “far” and “close” conditions, divided by action type. The descriptive statistics for the general RTs can be found in **Table 3**. The condition “far” showed statistically faster RTs in comparison to the “close” condition for both the “pointing” and “baseline” conditions (pointing:  $t(33) = 3.39, p = 0.002$ ; baseline:  $t(33) = 3.81, p = 0.0006$ ). The comparison was not statistically relevant for the “grasping” and “squeezing” conditions (grasping:  $t(33) = 1.52, p = 0.14$ ;

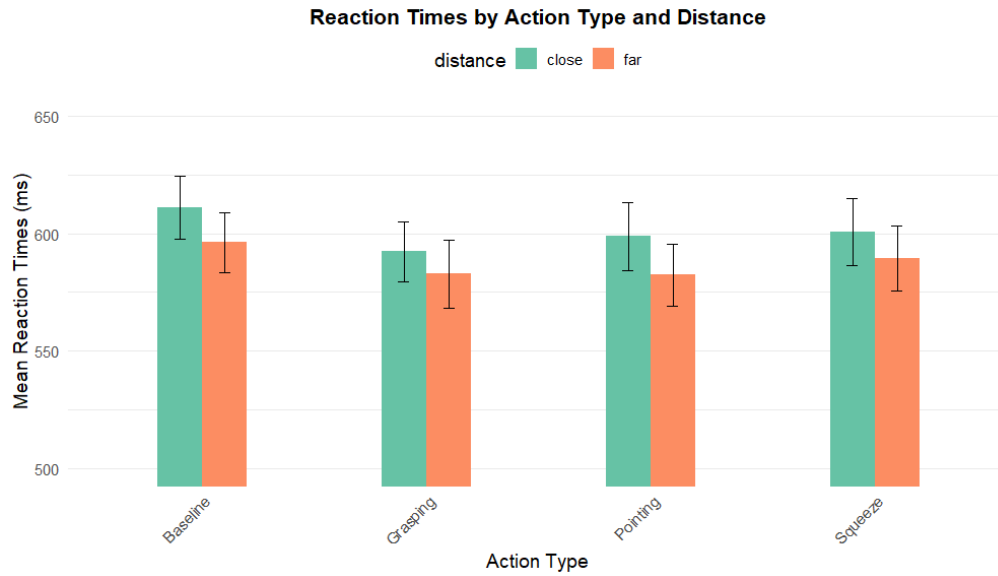
squeezing:  $t(33) = 1.96, p = 0.06$ ). Overall, the “far” condition showed faster RTs in comparison to the “close condition” ( $t(33) = -5.97, p < 0.0001$ ). These results are shown in **Figure 5**.

Looking at just the “action type” conditions, the grasping RTs were significantly faster in comparison to the sum of the other conditions RTs ( $t(33) = -2.39, p = 0.02$ ). Taken singularly, grasping RTs were also significantly faster than the baseline RTs, which were the overall slowest ( $t(33) = -2.38, p = 0.02$ ).

An ANOVA was run in JASP to analyse both the distance and type of action conditions, alongside their interaction. This analysis showed a significant effect of distance, while neither the action type nor the interaction was significant. These results are shown in **Table 5**.

	Mean	Median	SEM
Far	586,95	580,52	13,01
Close	600,24	595,48	12,89
Grasping	587,93	572,80	13,40
Pointing	590,25	585,39	13,60
Squeeze	595,35	597,71	13,61
Baseline	601,59	594,97	12,75
General	593,59	588,11	12,89

**Table 3.** The table illustrates the mean, median and Standard Error of the Mean (SEM) of the RTs for the close, far, grasping, pointing, squeezing and baseline conditions.



**Figure 5.** The figure illustrates the RTs of every action type condition, divided by the distance factor.

### Repeated Measures ANOVA

#### Within Subjects Effects

Cases	Sphericity Correction	Sum of Squares	df	Mean Square	F	p
Action	None	7382.798 <sup>a</sup>	3.000 <sup>a</sup>	2460.933 <sup>a</sup>	2.389 <sup>a</sup>	0.073 <sup>a</sup>
	Greenhouse-Geisser	7382.798	2.151	3432.937	2.389	0.095
Residuals	None	101991.057	99.000	1030.213		
	Greenhouse-Geisser	101991.057	70.969	1437.120		
Distance	None	12688.600	1.000	12688.600	40.036	< .001
	Greenhouse-Geisser	12688.600	1.000	12688.600	40.036	< .001
Residuals	None	10458.597	33.000	316.927		
	Greenhouse-Geisser	10458.597	33.000	316.927		
Action * Distance	None	840.149 <sup>a</sup>	3.000 <sup>a</sup>	280.050 <sup>a</sup>	0.513 <sup>a</sup>	0.674 <sup>a</sup>
	Greenhouse-Geisser	840.149	2.477	339.155	0.513	0.640
Residuals	None	54030.789	99.000	545.766		
	Greenhouse-Geisser	54030.789	81.747	660.951		

Note. Sphericity corrections not available for factors with 2 levels.

Note. Type III Sum of Squares

<sup>a</sup> Mauchly's test of sphericity indicates that the assumption of sphericity is violated ( $p < .05$ ).

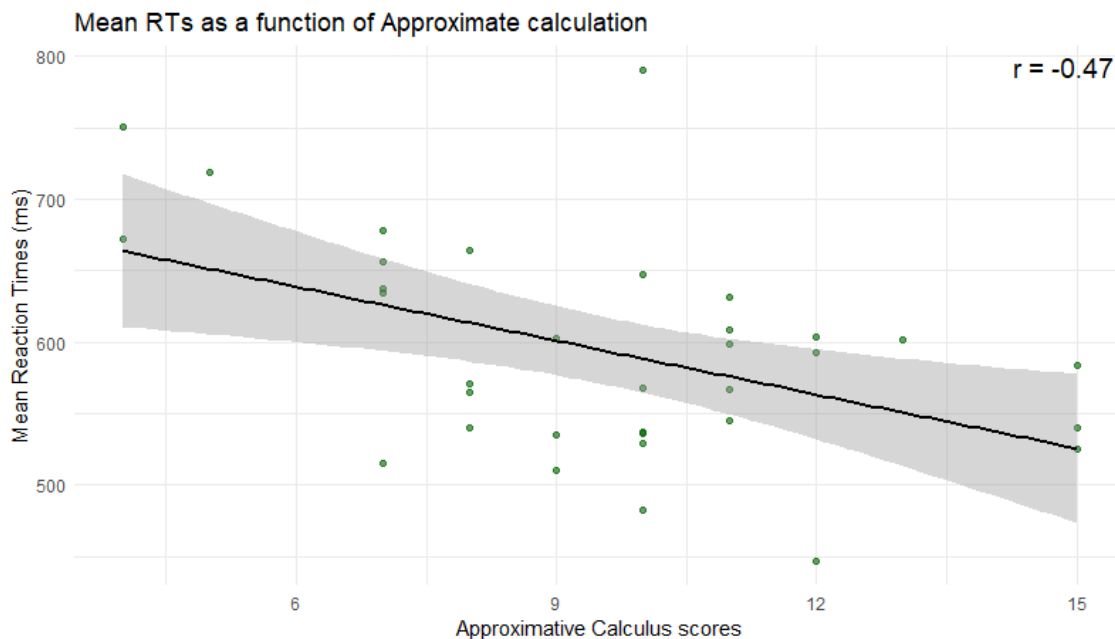
**Table 4.** Results show that the Distance factor is significant, while the Action factor and the interaction are not.

#### 4.2 Explorative analyses

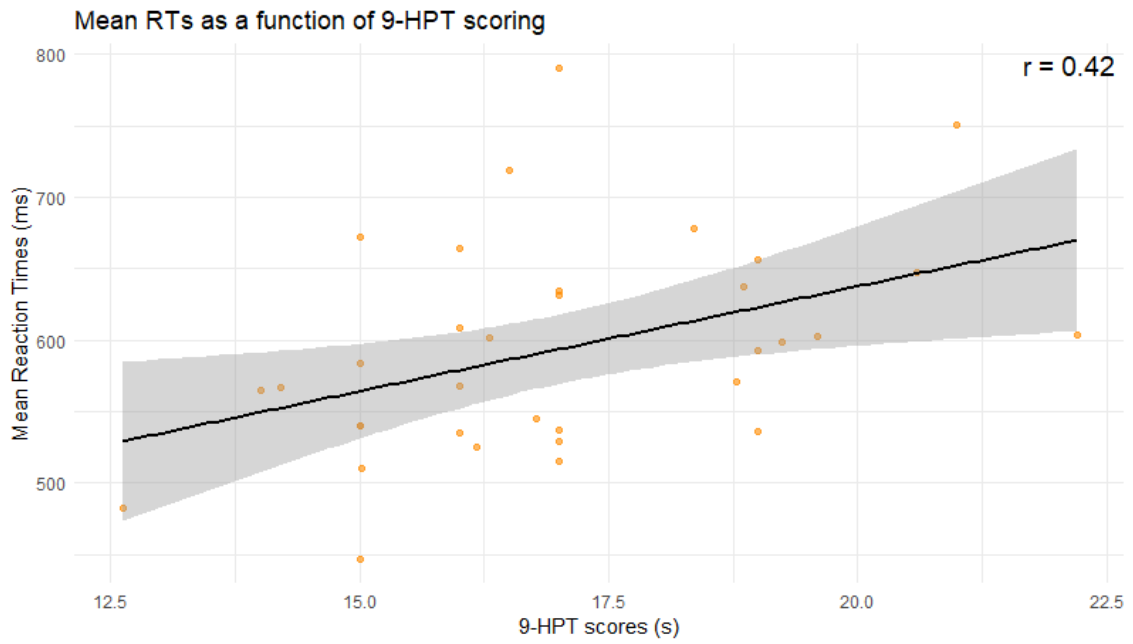
Although the effect of the action type factor is not statistically significant, it is close to 0.05. Thus, I investigated further what could have influenced this factor. Thinking about individual differences as an influencing factor, I looked at the correlations between the neuropsychological assessment we run beforehand and the cumulative RTs distribution. Pearson's correlation was used.

The following correlations are between the mean RTs of every participant and their score in different tests of the neuropsychological assessment (the tests in question are talked about in the “Neuropsychological assessment” paragraph). Out of the LSC-SUA battery, the Approximate Calculus section showed a strong inverse correlation, with  $r = -0.47$  ( $t(32) = -2.98$ ,  $p = 0.005$ ) This correlation is shown in **Figure 6**. The Approximate Calculus section consisted in 16 trials where participants were presented with complex calculations (e.g.:  $456'765 - 234'697$ ) and had to guess which of three given results was the right one, under one minute. The 9-Hole Peg Test showed a relevant correlation, but only for the right-hand results ( $r = 0.42$ ,  $t(32) = 2.63$ ,  $p = 0.01$ ) (**Figure 7**). The biggest correlation was found with the Purdue Pegboard Test. Both the right-hand and the left-hand, alongside the both-hands scoring showed a strong inverse correlation with the RTs. The “sum” scoring (the cumulative scoring of the right, left and both-hands tasks) correlated the most, with  $r = -0.57$  ( $t(32) = -3.93$ ,  $p = 0.0004$ ) (**Figure 8**).

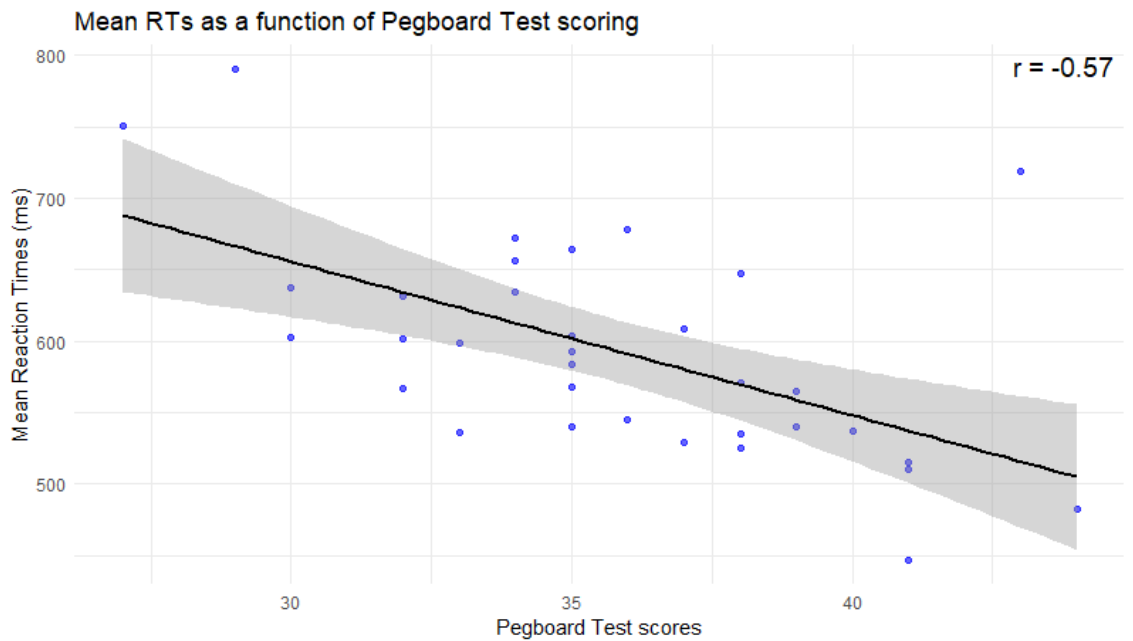
Notably, the complex assembly task did not show any relevant correlation.



**Figure 6** illustrates the correlation between participants main RTs and their relative scoring in the LSC-SUA: Approximative Calculus test. Note that a higher score in the test corresponds to a better performance.



**Figure 7** illustrates the correlation between participants main RTs and their relative 9-HPT scoring. Note that a higher scoring in the test corresponds to a worse performance, as the 9-HPT score is in seconds.



**Figure 8** illustrates the correlation between participants main RTs and their relative Pegboard Test scoring. Note that a higher scoring in the test corresponds to a better performance.

## **5. Discussion**

### *5.1 Main results*

In the work presented here, we investigated the influence of the hand actions of grasping and pointing on the numerical distance effect. The aim of this experiment was to further investigate the results of a previous study by Ranzini et al. (2022a), where the numerical distance effect appeared increased or decreased after a grasping or pointing action respectively, but only in small numbers (from 1 to 5). Thus, we attempted to replicate these results. In each trial, participants performed a hand action (grasping, pointing or squeezing) repeated 4 times, followed by 4 number comparison tasks. Participants also performed a baseline run both before and after the experimental blocks, which did not present a hand action task. We expected to see an increased distance effect (meaning a bigger gap in RTs between the close and far condition) in comparisons performed after a grasping action, and a close to zero gap in RTs in comparisons performed after a pointing action. These were respectively our first and second hypotheses.

The distance effect was present in the pointing condition, but it was not found in the grasping condition. Thus, the results appeared opposite to our hypotheses.

Although the results were not confirmed, it is worth noting that our paradigm presents many differences in respect to the previous study by Ranzini et al. (2022a). In the first place, our numerical range went from 1 to 5, while the previous study used a larger range: from 1 to 9. This was done with the intention to maximise the expected results. Moreover, the number of hand action repetitions was remarkably lower in our study: it was reduced from a previous 16 repetitions to just 4. Given the few hand action repetitions, the neural motor adaptation that we tried to induce might have not taken place. While the grasping action did not emphasize the distance effect as expected, it had an influence on the general RTs. The RTs for the grasping conditions were in fact the fastest overall. One explanation for this is that instead of a motor adaptation, the few action repetitions might have induced a priming effect (Ganel et al., 2006), since the grasping and number comparison neural networks share many common substrates (as seen in the paragraph “Common neural substrates”). Thus, the stimulation of the grasping network might facilitate the response to a subsequent number comparison task.

That said, I acknowledge that the analysis reported in this work are not exhaustive, and that different statistical approaches (e.g., linear mixed models) might be more suitable for

these data. Furthermore, it could be that the effect investigated here is influenced by individual differences. More sensitive analysis like linear mixed models could be more appropriate and accurate to interpret this type of data.

### *5.2 Secondary results*

Our exploratory analysis showed some interesting results. We tried to correlate the general RTs for every participant with the relative results of their neuropsychological assessment. Regarding the LSC-SUA battery (which tests numerical abilities), I found a big correlation between the Approximate Calculus section and RTs ( $r = -0.47$ ). Participants who performed better in the Approximate Calculus test were also generally faster in performing a number comparison task. This correlation is in line with ATOM and numerical embodied cognition (Sixtus et al., 2023), according to which the ability to approximatively estimate the result of complex mathematical operation (i.e.: LSC-SUA Approximate Calculus section) stems from the ANS, as does simple number comparison. More correlations were found with the manual dexterity tests: participants with faster RTs were also faster in the 9-Hole Peg Test and performed better in the Purdue Pegboard Test. Importantly, RTs correlated with all sub-sections of the Purdue Pegboard Test except for the Assembly section, which consists in a complex task.

These correlations are of particular interest because in this experiment the participants responded vocally. This could indicate a genuine correlation between number comparison skills (in this case the velocity in performing the task) and basic manual dexterity skills, as the ones required by the Purdue Pegboard Test and the 9-Hole Peg Test (i.e.: placing pegs into holes as fast as possible). The relation between number comparison and hand actions has been discussed in literature: in particular, grasping and number comparison seem to share common neural substrates (Ranzini et al., 2022b), which could be a cause of this correlation. In order to confirm these results, a similar experiment should be conducted introducing as control a non-numerical comparison task, were stimuli as not related to magnitude.

### *5.3 Limits*

It is important to note that some effects discussed here did not reach statistical significance. In addition, the paradigm used for this experiment differed from the previous study in many ways, thus impairing complete comparison. The numerical range used here was reduced, now going from 1 to 5 instead of 1 to 9. Also, number of repetitions of the

hand actions did not match the previous paradigm, now being 4 instead of 16. Moreover, participants were required to wear a cap to record their fNIRS activity throughout the whole experiment, which could have caused discomfort in performing vocal responses. To reduce movement artifacts, participants were instructed to move their mouth the least possible when responding. This could have affected their RTs.

## **6. Conclusion**

Our results seem to indicate a connection between grasping and number comparison: the RTs in a number comparison tasks were the fastest after a grasping action, and fast RTs correlate with high scorings in manual dexterity tests. These results could be due to the common neural substrates underlining number comparison and grasping, and support and embodied view of number cognition. The correlation between the RTs of the number comparison task and the scoring in an approximate calculus test also supports the view of the ANS as a common system underlining both number comparison and numerical approximation.

The results found here need further investigation in order to be confirmed, and we hope this will sprout further research.

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