UNIVERSITY OF PADOVA

Master’s degree in Cognitive Neuroscience and Clinical Neuropsychology

Final dissertation

Electrical Perspectives on Magnitude Processing: Investigating the Classical and Numerical Delboeuf Illusion

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1. Introduction

The human experience is inherently intertwined with the faculty of vision, a remarkable cognitive process that allows us to perceive, interpret, and interact with the world. As an integral aspect of daily life, vision forms the bedrock of our understanding and communication. It is a highly complex system that is formed by different components. Human beings get exposed to many visual parameters in everyday life such as shape, color, magnitude, light, and contrast. To derive meaning from the surroundings, the human visual system is able to process all these various forms of visual information.

Size and magnitude significantly impact how the world is perceived because they help humans form perceptions of it. The sense of size, a basic component of visual processing, affects a range of daily experiences and social relationships. Professionals in neuropsychology and neurology must comprehend the significance of scale and size in visual perception since studying these aspects clarifies how the human brain processes visual information, comprehends the environment, and as a result how the decisions and actions are impacted by these aspects.

The role of size perception proves its importance in depth perception, object recognition, and spatial relationships. Size perception provides a critical cue for object recognition, estimating the distance of the object in a scene, and motor actions, and interactions. Some conditions can alter size perception in humans such as depth, contrast, color, and light.

1.1.What is Illusion?

Richard Gregory (2009) defined illusions as “departures from reality” —in other words, illusions are situations where what we perceive does not correspond to what is “out there”.Woodworth (1938), in a widely recognized textbook of experimental psychology, defined illusions as “errors in apparent length, area, direction or curvature which occur in the perception of patterns of lines” (p. 643). It is extraordinarily hard to give a satisfactory definition of an `illusion'. It may be the departure from reality or truth (Gregory, 1997). Illusions can take on various forms and impact our perceptions, cognition, and comprehension of life. Distortion of the senses and mind leads to a misinterpretation of reality. This misinterpretation can manifest in various ways: including sensory experiences, cognitive processes, and existential beliefs. Recognition of biases influencing judgment and decision-making is made easier by an understanding of cognitive illusions, which promotes more logical and informed thought processes.

Illusions are essential for exploring and questioning the nature of existence, knowledge, and reality. They push us to look beyond the apparent and immediate, seeking a deeper understanding and confronting the limits of our perceptions and cognitive abilities. This exploration often leads to profound insights about the nature of truth and the foundations of our beliefs.

1.1.2. Visual Illusions

There is some difficulty in rigorously defining ‘illusion’, as there is a sense in which all vision is an illusion (Eagleman, 2001). Sensory illusions, and in particular illusions of the visual sense, have been known for a very long time (Wade, 2017). Illusory displays tend to cause bemused puzzlement and pleas for explanation by casual viewers and have attracted the attention of psychologists, philosophers, neuroscientists, physicists, and artists (Todorović, 2020). Most of the well-known illusions can be considered to be either perceptual distortions of magnitude (length or size) or perceptual distortions of direction of lines (Rock, 1975). There is a parallel literature on illusions in the writings of philosophers. McLaughlin (2016) characterized illusions as follows: “Sometimes something looks some way to us that it isn’t.

How it looks is not how it is. That happens whenever we have a visual illusion". Smith (2005) defined an illusion as "any perceptual situation in which a physical object is actually perceived, but in which that object perceptually appears other than it really is".

Visual illusions highlight how easily contextual cues, shapes, and lines can trick our brains into believing something different than it is. They draw attention to the intricate mechanisms underlying visual perception and the way our minds create the visual environment. There are many examples of visual illusions. Two of them are the Delboef Illusion and the Ebbinghaus Illusion (See Figure 1).

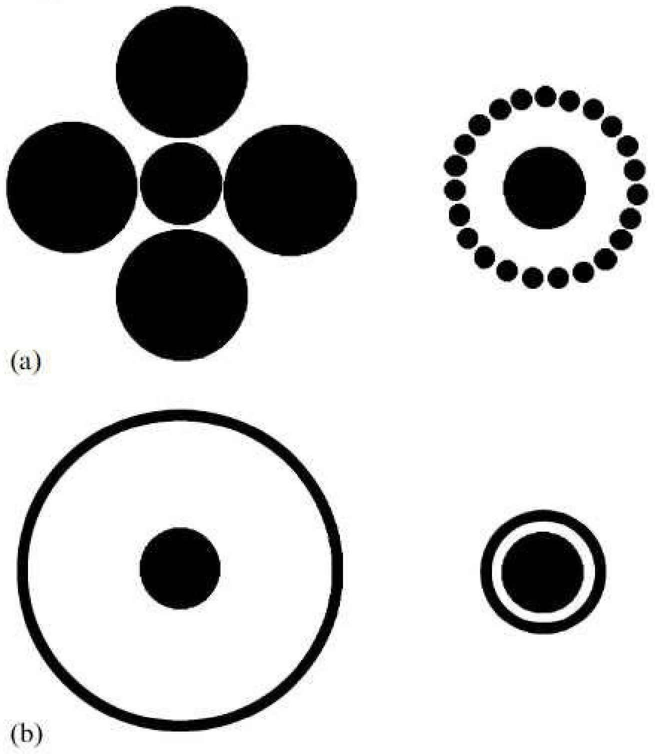

Figure 1. (a) The Ebbinghaus Illusion. (b) The Delboeuf Illusion. (Roberts et al. 2005)

Figure 1a illustrates its most popular form, as it appears most often in general textbooks. In this form, it is often used to illustrate a simple size-contrast effect, where large inducers make an object appear smaller, while small inducers make it appear larger (Obonai,1954). The Ebbinghaus illusion is not a straightforward geometric trick, and it may require multiple processes to achieve varying degrees of effect such as distance between the central target and the inducers. Depending on this distance, perceived space might be compressed or expanded, or neighboring con-tours might attract or repel each other, resulting in a distortion of the perceived size of the elements (Roberts et al. 2005). This type of spatial interaction might also account for the Delboeuf illusion (Delboeuf, 1892), which is closely related to the Ebbinghaus illusion. In this illusion, illustrated in Figure 1b, the central target appears larger when the inducing ring is close and smaller when it is distant.

1.1.3. Delbouef Illusion

The Delboeuf illusion is a visual illusion that involves a false perception of the relative size of identical circles when surrounded by larger circles of different sizes. In this illusion, two identical central circles are placed inside larger surrounding circles (or rings). One central circle is surrounded by a larger outer circle, while a smaller outer circle surrounds the other. Although the middle circles are the same size, the circle surrounded by the larger outer circle appears smaller and the circle surrounded by the smaller outer circle appears larger. This illusion highlights how context or surrounding elements can affect our perception of size. This is similar to other context-based illusions, such as the Ebbinghaus illusion, where the size of surrounding objects affects the perceived size of the central object. The Delboeuf illusion is often used in visual perception and cognitive psychology research to study how the human brain processes size and spatial relationships.

Researchers have been trying to apply the Delboeuf illusion to different topics. As an example, food consumption, portion size perception, and how to reduce food waste. According to a study by McClain et al. (2014), plate design can influence food perception and potentially aid in weight control strategies (See Figure 2). Another study explores Delboeuf Illusion's impact on food perception. Research by Wansink and van Ittersum (2013) highlights how plate size affects food consumption norms (See Figure 3). Dinnerware size serves as a visual anchor for appropriate fill levels, impacting how much food is served and consumed. They revealed that large plates led to 52% more food served, 45% more eaten, and 135% more wasted. With the enlightenment of these results, smaller dinnerware can help control consumption, reduce waste, and increase profitability in the food industry.

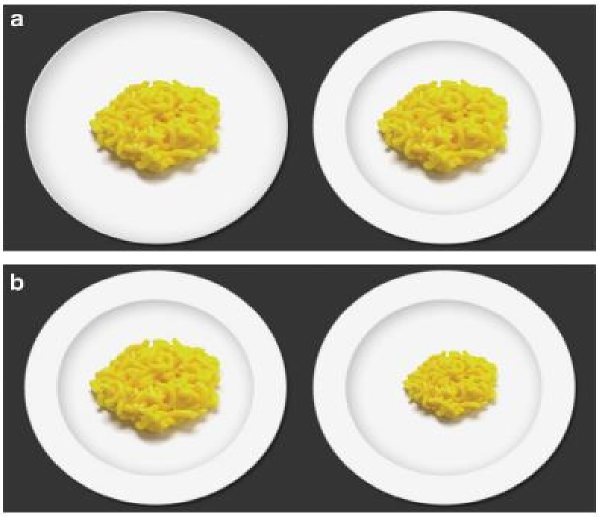

Figure 2. Examples of pictures used as stimuli. (**a**) Standard stimulus (that is, food size of 185 pixels on a plate with a 1/3 rim width-to-plate radius proportion) is on right; rimless plate with same food size is on left and (**b**) standard stimulus is on left; same rim size with smaller food size is on right.

Figure 2. McClain, A., van den Bos, W., Matheson, D. et al. (2014) Visual illusions and plate design: the effects of plate rim widths and rim coloring on perceived food portion size. *Int J Obes 38*, 657–662.

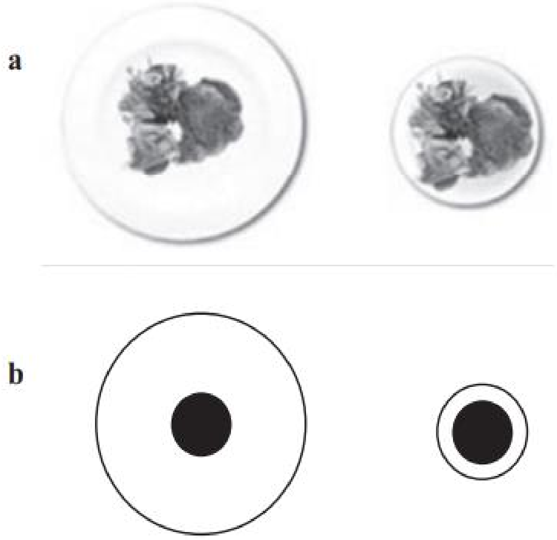

Figure 4. Dinnerware size and the Delboeuf illusion. *a*. Food on large versus small plate. *b*. Delboeuf illusion.

Figure 3. Wansink, Brian & Ittersum, Koert. (2013). Portion Size Me: Plate-Size Induced Consumption Norms and Win-Win Solutions for Reducing Food Intake and Waste. *Journal of experimental psychology.* Applied. 19. 320-32.

1.2.Numerical Estimation

Another subject of our experiment that sheds light on discovering our visual perception mechanisms is numerical estimation. Research on human numerical estimation examines how individuals perceive, estimate, and interact with quantities without performing precise computations. The ability to estimate the number of elements in a set without counting all of them individually makes numerosity estimation crucial. For many daily activities, such as predicting crowd sizes, and object numbers, or making judgments based on figures, this ability is crucial. Discriminating between quantities allows individuals to make optimal decisions in their natural environments in several ecological contexts, such as foraging, mating, and antipredator strategies. Understanding how people estimate numerosity can help us better understand how our perception of quantity is influenced by visual cues and cognitive processes (Santacà et al. 2023). Visual illusions provide valuable insights into how numerosity estimation is influenced by perceptual context. Several studies have demonstrated that visual illusions, such as the Müller-Lyer illusion, can affect numerical judgements. For instance, the Müller-Lyer illusion, where lines of the same length appear different due to the direction of arrowheads at their ends, also affects the perceived numerosity of dot arrays aligned along these lines (e.g. Dormal, Larigaldie, Lefèvre, Pesenti&Andres, 2018). The research by Dormal et al. (2018) explored how perceived length impacts numerosity estimation using the Müller-Lyer illusion. The study found that perceived, rather than actual, length influences numerosity judgments. In the first experiment, participants compared the number of dots in arrays with inward- or outward-pointing arrows. When arrays of equal length appeared different due to the illusion, participants incorrectly reported different numbers of dots. This effect vanished when the actual lengths were adjusted to account for the illusion. The second experiment required participants to verbally estimate the number of dots in single arrays. Estimations were higher for arrays with outward-pointing arrows, indicating that perceived length influenced numerical estimates even without the need for a comparative choice. Overall, the findings suggest that visual illusions affecting perceived length can influence numerosity estimation, highlighting an interaction between visual perception and numerical processing.

Another study by Santaca&Granziol (2018) revealed that human participants showed a clear influence of the Delboeuf illusion on their numerical estimations. When presented with two identical arrays of dots within different-sized backgrounds, participants perceived the array within the smaller background as more numerous compared to the one within the larger background. This effect aligns with the classical perception of the Delboeuf illusion, where a target within a smaller context is overestimated in size, thus appearing more numerous. The findings provide insights into the evolutionary and functional aspects of numerical cognition, highlighting the complex interplay between perceptual and cognitive processes. Before going further, it is necessary to introduce the visual system and transcranial electrical stimulation.

1.3.Visual Pathway

The neural mechanisms of vision in humans constitute a complicated and highly coordinated process, beginning with the transduction of light into neural signals within the eye and culminating in the perception and interpretation of visual stimuli by the brain. Initially, light enters the eye through the cornea and lens, which focus it onto the retina. The retina houses photoreceptor cells, specifically rods, and cones, responsible for detecting light. Rods are highly sensitive to low light conditions and are critical for scotopic (night) vision, whereas cones are involved in photopic (daylight) vision and are essential for color discrimination and high spatial acuity. After absorption by a photoreceptor, the photoreceptor converts the light into an electrical signal via a phototransduction pathway. These signals are sent through the bipolar cells to the ganglion cells, whose axons form the optic nerve. The optic nerve merges into the optic chiasm, an important interstation of the visual system, where one part of the visual information that has been registered by each eye will be led to the contralateral hemisphere while the other part of information remains on the ipsilateral hemisphere. Following this, the majority of the optic nerve fibers project to the lateral geniculate nucleus (LGN) of the thalamus. The lateral geniculate nucleus of the thalamus is located posterolateral to the pulvinar and is the main input to the visual cortex (Swienton & Thomas, 2014). The LGN, which is part of the thalamus, consists of six layers with layer 1 and 2 belonging to the magnocellular system and layers 3 to 6 belonging to the parvocellular system. The magnocellular and parvocellular pathways are two of the core pathways of conscious visual perception (Masri, Grünert, & Martin, 2020). They are essential for the parallel processing of visual information which differs, for instance, in temporal frequency (e.g. motion) or spatial frequency (e.g. fine detail; Contemori, Battaglini, Barollo, Ciavarelli, & Casco, 2019). The LGN acts as a critical relay center, further processing and integrating visual information before transmitting it to the primary visual cortex (V1) located in the occipital lobe.

Area V1 plays a critical role in visual information processing because most visual information ultimately reaching the rest of the visual cortex is first funneled through V1 (Felleman&Essen, 1991; Tootell et al. 1998). Later stages of visual processing occur in higher visual areas, including V2, V3, V4, and V5/MT. Each area is specialized to analyze different aspects of visual stimuli, such as shape, color, and movement. The processed information is then divided into two primary streams: the dorsal stream, which is involved in spatial processing and motion detection ("where" pathway), projecting to the parietal lobe, and the ventral stream, which is responsible for object recognition and form processing ("what" pathway), projecting to the temporal lobe (Hebart&Hesselman, 2012).

Visual information is integrated across various pathways and regions, utilizing feature detectors in the visual cortex. These detectors respond to specific elements such as edges, orientations, and motion, allowing for simultaneous processing of multiple visual attributes. This synchronized neural activity tackles the binding problem by ensuring that disparate visual information is combined to create a unified perceptual experience. Therefore, the intricate and dynamic neural circuitry of the human visual system enables the translation of raw sensory input into precise and meaningful visual perceptions.

1.4.Transcranial electrical stimulation

Transcranial electrical stimulation (tES) is a group of neuromodulatory techniques in which low voltage constant or alternating currents are applied to the human brain via scalp electrodes (Bestmann&Walsh, 2017). These methods, including transcranial direct current stimulation (tDCS), transcranial alternating current stimulation (tACS), and transcranial random noise stimulation (tRNS), have gained prominence in both clinical and research settings for their potential to influence cognitive functions, motor skills, and neuroplasticity. In tES, electrodes placed on the scalp are used to deliver controlled electrical currents to specific areas of the brain. The main goal is to change the excitability of neurons and thus modulate brain activity, and ability to influence the electrical environment of neurons. This modulation can improve or inhibit nervous system functions depending on stimulation parameters such as intensity, duration, and frequency of the electric current (See Appendix A). The method of using stimulation is similar for all low-intensity tES interventions. Current is provided by a battery-powered stimulator using a pair of rubber electrodes wrapped in a sponge soaked in isotonic saline. The stimulation protocol differs between different types of stimulation techniques. For example, tDCS induces a low-intensity electric field that occurs at a threshold level, while tACS uses an alternating electric current that results in sinusoidal fluctuations in membrane potential (Antal & Paulus, 2013).

1.4.2. Transcranial alternating current stimulation

The primary mechanism by which tACS influences brain activity is through the entrainment of neural oscillations (Herrmann, Rach, Neuling&Strüber, 2013). Neural oscillations are rhythmic patterns of neuronal activity that are crucial for various brain functions, including perception, attention, memory, and motor control (Antal & Herrmann, 2016). Different frequencies of tACS can target distinct neural oscillatory bands, such as delta (1-4 Hz), theta (4-8 Hz), alpha (8-12 Hz), beta (12-30 Hz), and gamma (30-100 Hz) bands (Antal & Herrmann, 2016). Each of these frequency bands is associated with different cognitive and behavioral states (Fröhlich, 2014). tACS applied at conventional electroencephalography (EEG) frequencies (0.1–80 Hz) and in the so-called "ripple" range (140 Hz, see below) (Moliadze et al., 2010) may be able to interact with ongoing rhythms in the cerebral cortex. When stimulating the left frontal and parietal cortex by 6 Hz tACS in phase, cognitive performance in a delayed letter discrimination task was improved, when stimulating out of phase it was delayed (Polania et al.,2012; Antal&Paulus, 2013). tACS applied in the EEG domain is thought to primarily entrain or synchronize networks of neurons, causing changes in ongoing oscillatory brain activity (Antal&Paulus, 2013). What exactly is brain oscillation? Brain oscillations, also known as neural oscillations, refer to the rhythmic or repetitive electrical activity generated by neurons in the central nervous system. These oscillations can be observed in the brain's electrical activity and are measured using electroencephalography (EEG) or magnetoencephalography (MEG).

Transcranial alternating current stimulation influences vision and induces visual illusions by entraining neural oscillations within the visual cortex. Through frequency-specific balance, tACS can upgrade visual sensitivity, induce phosphenes, and change the recognition of visual illusions.

Transcranial alternating current stimulation (tACS) is another approach that has the potentiality to shed light on the causal link between neural oscillations and perception (Battaglini, Ghiani, Casco, Melcher & Rosconi, 2020). Some studies demonstrate that tACS, possibly driving the activity of cortical regions to the external frequency imposed by tACS, represents an efficient method to determine significant entrainment of the brain's cortical oscillations during and after the stimulation (Fröhlich and McCormick, 2010; Helfrich et al., 2014; Battaglini, Ghiani, Casco, Melcher & Rosconi, 2020). Helfrich et al. (2014) reported that alpha-tACS enhances visual detection performance by modulating oscillatory power in the visual cortex. Numerous studies have investigated specific frequencies through various stimulation techniques, aiming to enhance perceptual tasks of different kinds. For example, in visual recognition tasks, a reduction in the contextual effects of visual stimuli has been observed through changes in beta wave frequencies (Battaglini, Ghiani, Casco&Rosconi, 2020). Visual crowding, where surrounding elements interfere with target identification, can compromise stimulus perception (Levi, 2008). Battaglini et al. (2020) explored how transcranial alternating current stimulation (tACS) applied to parietal areas at specific frequencies modulates visual crowding. Visual crowding typically leads to excessive integration, occurring either at an early stage of processing (elementary feature binding phase) or at a higher level mediating contour integration (V4). Hypotheses were formulated based on previous articles (Ronconi & Bellacosa Marotti, 2017; Ronconi, Bertoni & Bellacosa Marotti, 2016) that observed an inverse correlation between visual crowding performance and the number of beta waves (15-30 Hz., typically associated with parietal cortex activation). Building on results showing the modulatory potential of tACS on neural oscillations, this study applied an 18 Hz. frequency to reduce visual crowding. Twenty healthy participants were recruited to perform a target orientation recognition task with concurrent tACS at 18 Hz. (beta waves), 10 Hz. (alpha waves), and Sham (no stimulation) as control conditions. Stimulation was applied using a hybrid system allowing both EEG signal recording and stimulation. Eight electrodes were mostly placed on the right side of the scalp in the parietal region. Additionally, the study investigated whether there was an association between the specific phase of 18 Hz. tACS and task performance accuracy. Results confirmed the initial hypothesis: participants exhibited better performance in recognizing the contralateral target stimulus and discriminating its features (orientation) when receiving 18 Hz. stimulation compared to 10 Hz. or Sham. The data suggest a specific frequency characterizing parietal cortex activity during a visual crowding task. These findings align with previous studies highlighting the fundamental role of beta waves in parietal cortex excitability, while alpha waves seem more correlated with activity in occipital areas. No significant modulation of task accuracy based on the tACS phase was observed, contrary to some studies suggesting that a stimulus may be processed more accurately during a specific phase associated with increased neural excitability depending on the stimulation frequency used (mostly within the alpha or theta range). However, clear correlations between a specific phase of beta oscillations and increased neural excitability have not yet emerged. Nevertheless, the stimulation effect was confirmed by comparing the EEG traces recorded before and after stimulation: modulation of beta band power following tACS indicated neural entrainment, where a population of neurons aligns and resonates at the stimulation frequency.

In conclusion, beta-frequency tACS stimulation on the parietal region of the brain appears to enhance perception, particularly in visual crowding situations. This study has clarified the neural mechanisms underlying this crucial aspect of vision. The findings may have implications for the treatment of visual dysfunctions related to crowding through the development of new non-invasive therapies based on brain stimulation.

Another noteworthy study involving electrical stimulation is that of Stonkus and colleagues (2016). The hypothesis of this study is that by stimulating specific areas underlying the figure contour integration process at a frequency of 7 Hz. using tACS, performance could improve. This idea is formulated based on previous EEG studies' results indicating that communication between lower visual perception areas in the left occipital cortex and higher-order areas in the right intraparietal sulcus (involved in the integration process) is mediated by theta oscillations (Hanslmayr et al, 2013; Cabral-Calderin et al., 2020).

The study included twenty-one participants with normal or corrected vision who underwent stimulation conditions where the frequency was 7 Hz. The authors observed improved performance compared to the placebo (sham) condition. These recent results suggest that tACS can not only influence local oscillatory activity but can also manipulate phase synchrony between distant brain regions, and this modulation affects cognition.

Many other studies show how tACS can modulate visual performance. For example, alternating current stimulation at 60 Hz. increases the number of perception changes in an ambiguous figure (Cabral-Calderin et al., 2015). tACS at 10 Hz. seems to improve the integration processes of visual stimuli temporally (Battaglini, Mena, Casco & Ronconi, 2020). Even though additional research is needed on how tACS correlates with visual perception, these researchers shed light on future researchers with their findings.

1.5.Research Question

This study investigates the potential existence of a generalized magnitude system assessing if the same perceptual bias affects in the same way different magnitude processing. Moreover, participants underwent three transcranial alternating current stimulations (tACS) at different frequencies (7 Hz, 18 Hz, and sham) to explore whether it can affect quantities processing in the classic Delboef illusion and whether it can have the same effect as its numerosity counterpart. Specifically, according to previous findings, we hypothesize that theta-frequency tACS will increase visual integration, strengthening the illusion, whereas beta tACS will reduce illusion strength by increasing visual segregation. These hypotheses are aimed at exploring the cognitive processes and neural mechanisms involved in perceiving and processing quantities, as well as the potential influence of non-invasive brain stimulation techniques on these processes.

2. Methods

2.1.Participants

For this study, 48 adult volunteers (38 females, 10 males; mean age ± SD = 24.19 ± 3.02 years), all of whom were University of Padova students pursuing either a bachelor's or master's degree were recruited. All participants reported having normal or corrected-to-normal vision. Eligibility for transcranial electrical stimulation was assessed through a pre-screening test (see Appendix B) conducted at the beginning of each session. Exclusion criteria for the study include neurological disorders affecting visual and/or numerical abilities, substance abuse, and any medical condition posing a risk to participants (e.g. pacemaker, epilepsy, migraine auras). Not all participants met the criteria for receiving tACS so they were excluded. Consequently, the final sample consisted of 34 participants (age range = 21-35 years, 5 males). A post-stimulation questionnaire (see Appendix C) was administered at the end of each session to ensure participant well-being and to evaluate whether they anticipated receiving true stimulation or a placebo (i.e., no stimulation; see Fertonani et al., 2015). Before taking part in the experiment, participants were given an informed consent form in compliance with the Declaration of Helsinki. The present study has been approved by the Ethics Committee of the Department of General Psychology of the University of Padua, Italy.

2.2.Experimental set-up and tACS stimulation

The study was conducted in a dimly lit room to minimize the detection of tES-induced phosphenes (Evans et al., 2022). Participants were instructed to use a chin rest positioned 57 cm away from the monitor. The stimuli were displayed on an LCD ASUS monitor with a resolution of 1280 × 1024 and a refresh rate of 60Hz. tACS was administered over the parietal areas using a BrainSTIM device (BrainSTIM, EMS, Bologna, Italy) at an intensity of 1 mA. Carbonized rubber electrodes, measuring 5 × 5 cm and covered in sponges The two electrodes were inserted into prior with saline solution-soaked sponges to decrease the impedance e.g., to enhance the conductivity and placed at the locations corresponding to P3 and P4 on a 64-channel EEG cap arranged according to the international 10-20 system. In the real conditions, the current was applied for 20-30 minutes (with 10-s fade-in and -out periods at the stimulation's beginning and end). In the sham tACS, the current was turned off 10 seconds after the beginning of the stimulation (with 10-s fade-in and –out periods, for a total of 30 s). The majority of the participants reported experiencing absence or low level of fatigue during the test, independently on the stimulation type ($\chi^2_9 = 8.14$, $p = 0.52$). No phosphenes were reported. Moreover, they were not able to discriminate between real stimulation and placebo, as confirmed by a Pearson's Chi-Square test for frequency distribution ($\chi^2_1 = 1.76$, $p = 0.18$; the observed probability of reported 'stimulation present' was 0.60 in the 7Hz tACS condition, 0.52 in the 18Hz tACS condition and 0.75 in the sham condition). Stimulation parameters were selected in accordance with the safety guidelines provided by Antal and colleagues (2017).

2.3.Stimuli

Two distinct types of stimuli were used. For the numerical discrimination task, the stimuli consisted of two arrays of orange squares set within white circular backgrounds, placed inside black rectangles (Figure 4). In contrast, for the continuous quantity discrimination task, the stimuli consisted of two orange circles within white circular backgrounds, which were also enclosed within black rectangles measuring 4.5 × 4.5 cm, similar to those used in the numerical discrimination task (Figure 4).

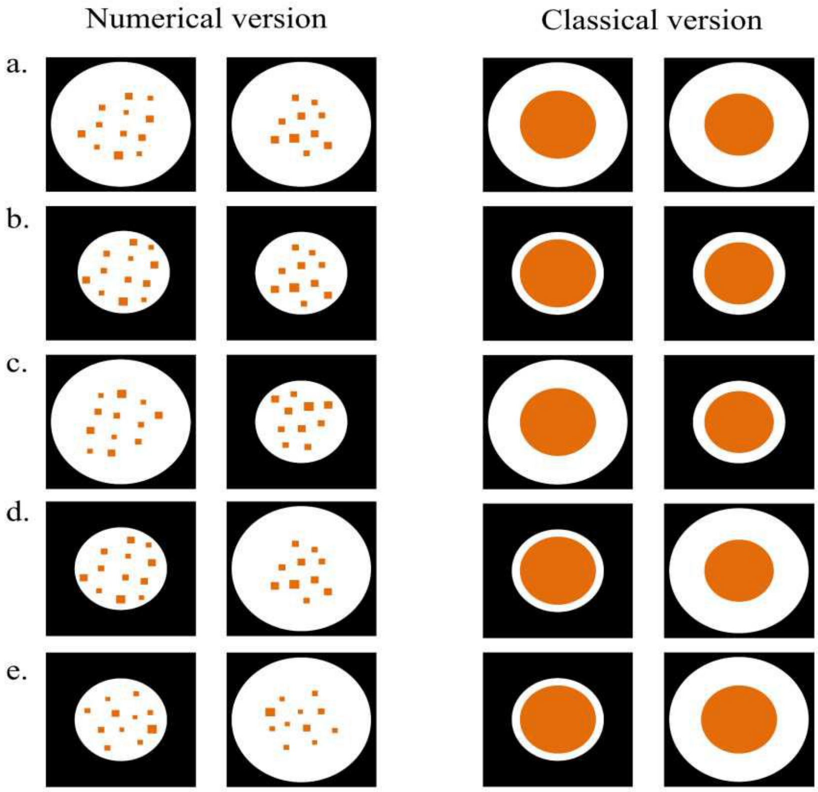

Figure 4. Images of the stimuli that are used in the experiment

For each discrimination task, we organized two types of trials: control trials and illusory trials. In control trials, there was a real difference between the two stimuli: 10 squares versus 12 squares for numerical discrimination (a ratio of 0.83), while for continuous quantity discrimination, the circles' areas differed by the same ratio. Four different combinations of numerosity/circles and backgrounds were used, based on a previous study (Santacà & Granziol, 2023). In ‘large trials’, the two target stimuli were presented in identical large backgrounds (4.22 cm in diameter; Figure 4a). In ‘small trials’, the stimuli were presented in identical small backgrounds (2.79 cm in diameter; Figure 4b). The remaining trials used different backgrounds for each pair of stimuli. In ‘congruent trials’, the larger target stimulus was in the large background, and the smaller stimulus was in the small background (2.79 cm and 4.22 cm in diameter; Figure 4c). In ‘incongruent trials’, the large background contained the smaller stimulus, and the small background contained the larger stimulus (2.79 cm and 4.22 cm in diameter; Figure 4d). Illusory trials involved the same number of items or the same circles presented in different backgrounds (one large and one small, 2.79 cm and 4.22 cm in diameter; Figure 4e), mimicking the numerical or classical Delboeuf illusion. For numerical discrimination, six different pairs for each type of control trial and illusory trial, varying the position and size of the squares were arranged. The sides of the squares ranged from 0.15 cm to 0.30 cm. Similarly, for continuous quantity discrimination, six different pairs for each type of control trial and illusory trial, with the diameters of the circles ranging from 1.64 cm to 2.35 cm were arranged.

As detailed in the previous study by Santacà and Granziol (2023), assessing numerical discrimination poses a challenge because numerosity naturally covaries with other physical properties, such as the total area of all elements in a stimulus, the size of the elements, the overall space they occupy, and their density. To ensure that participants did not base their decisions on these other attributes, these variables in the control trials, as explained comprehensively in Santacà and Granziol (2023), and presented the same numerosity in the illusory trials were controlled. This way, the results of the illusory trials would solely reflect the direct effect of the Delboeuf illusion on numerosity estimation, rather than any indirect impact from biased perception due to other physical attributes. Additionally, to minimize the risk of participants noticing that the squares in the two illusory arrays were identical in size and location, each numerosity array in the illusory trials was rotated.

2.4.Procedure

Each experimental session consisted of two blocks: one with numerical stimuli and the other with continuous quantity stimuli (circles). Each block comprised 300 trials and lasted approximately 20 minutes, with a 5-minute break in between, resulting in a total session duration of 45 minutes. The order of trial types was randomized for each session. Participants received both oral and written instructions before the experiment began. During the session, participants were presented with pairs of stimuli of the same type (numerical or continuous quantity discrimination) positioned 8 cm apart. Using a QWERTY keyboard, they indicated which stimulus appeared more numerous or larger, depending on the discrimination task. Specifically, participants pressed the “S” button for the stimulus on the left side of the screen and the “L” button for the stimulus on the right side.

A fixation cross appeared at the center of the screen for 250 ms at the beginning of each block. Participants were instructed to maintain their gaze at the center of the screen during each block. Paired stimuli were displayed for 150 ms, a duration too brief to allow for saccadic eye movements toward the target position or verbal counting during numerical discrimination. After the stimulus presentation, a white screen appeared for 550 ms, during which participants made their choice.

The experiment comprised three sessions for each participant, conducted on non-consecutive days at least one week apart. In each session, participants performed both discrimination tasks under different stimulation conditions. Specifically, participants experienced a placebo/control condition with no stimulation and two other conditions with stimulation at different frequencies: 7 Hz. and 18 Hz. The assignment of these stimulation conditions was randomized across sessions, ensuring that each participant experienced all conditions in a different order.

2.5.Statistical Analyses

Data were analyzed in R version 3.5.2. For all three stimulations (7Hz, 18Hz, sham), accuracy in terms of selecting the larger target stimulus and numerosity for control trials were recorded. In illusory trials, choices for the stimulus and the numerosity displayed in the small context were scored as ’correct’. At the individual level, to compare the choices for the larger target stimulus, numerosity in control trials, for the stimulus, and the numerosity presented in the small context in illusory trials, binomial tests were used (chance level = 0.5). Frequency of choices for the larger target stimulus, numerosity in control trials, for the stimulus, and, the numerosity presented in the small context in illusory trials group analyses were performed. Not all data were normally distributed (Shapiro–Wilk test, $p < 0.05$); thus, one-sample t-tests or Wilcoxon-signed rank tests were performed (chance level = 0.5).

Considering only the sham condition, a Pearson correlation test was performed to assess the correlation between the performances of the two discriminations (numerical vs. continuous quantity discrimination) both considering only those control trials in which the Delboeuf illusion has no effect (small and large trials) and only those trials in which the illusion should have an effect (congruent trials, incongruent trials, illusory trials).

Accuracy of responses by fitting a generalized mixed-effects model for binomial distributions (GLMM) with three variables: the stimulation (7 Hz, 18 Hz, or sham), the discrimination (numerical or continuous quantity), and the stimulus type (large, small, congruent, incongruent or illusory trials) were also assessed. Each variables were fitted, as well as their two- and three-way interactions, as fixed effects whereas we fitted subjects as clustering variables and random factors (i.e., random intercept model). Sum contrasts were set for the three abovementioned predictors. GLMMs were estimated with a Maximum Likelihood (Laplace Approximation) procedure with the function glmer() from the *lme4* package (Bates, Maechler, Bolker&Walker, 2015). Whenever a main effect emerged as statistically significant (the Anova () function of the car package was used; (Fox et al. 2012), post hoc comparisons were performed with the function emmeans () from the *emmeans* package (Lenth et al., 2023).

Considering the number of comparisons that could arise from high-order effects such as interactions, not all the comparisons were analyzed. In particular, the differences inside one variable along another variable were selected (see Appendix E: Table S2). In this way, it was reduced the chance of committing Type I error due to comparisons that were beyond the aim of the present work. Nonetheless, the False Discovery rate method (Benjamini&Hochberg, 1995) was used to adjust post-hoc comparisons. For each comparison, Odds Ratios (ORs), their 95% confidence intervals (CI), statistics (z), standard error (SE), and p-values (p) are also reported. As suggested by several works (Harris, 2021; Lenzi, Furlong, Dowdy, Sharkey, Gini&Altoè, 2015), when reporting OR, the outcomes may be presented in two different formats: as a percentage difference in likelihood, which is calculated by subtracting the Odds Ratios from 1.0, and as “n times less/more likely”, which is determined by dividing 1.0 by the OR in the former case (i.e., “less”). In the present research, the latter way was preferred, since ORs below 1.0 may be less straightforward and intuitive for interpreting the strength of associations compared to ORs above 1.0. Overall, three different GLMMs were performed: two models tested the interaction between the stimulus type and the stimulation only in the numerical discrimination or only in the continuous quantity discrimination. Lastly, an overall model were performed including the discrimination type with the two former predictors.

3. Results

3.1.Behavioral level: sham condition

Numerical discrimination

For the numerical discrimination, individual analyses revealed that 23 out of 34 participants selected the larger numerosity significantly more than chance in control trials (mean ± SD = 61.00 ± 9.16 %; Appendix D: Table S1). Considering the Delboeuf illusory trials, 9 out of 34 participants selected the numerosity presented in the small context significantly more than chance whereas, interestingly, 5 selected more than chance the one presented in the large context (mean ± SD = 54.51 ± 16.51 %; Appendix D: Table S1). Group analyses revealed that participants selected the larger numerosity significantly more than chance in control trials (mean ± SD = 62.35 ± 8.30 %; Wilcoxon-signed rank test, Z = 0.98, p <0.001*). Overall, participants did not perceive the numerical Delboeuf illusion, since they did not select any numerosity significantly more than chance (mean ± SD = 54.51 ± 16.85 %; one-sample *t-test*, $t_{33} = 1.56$, $p = 0.128$).

Continuous quantity discrimination

Individual analyses revealed that 23 out of 34 participants selected the larger target stimulus significantly more than chance in control trials (Appendix D: Table S1). Considering the Delboeuf illusory trials, 27 out of 34 participants selected the stimulus presented in the small context significantly more than chance (Appendix D: Table S1). Group analyses revealed that participants selected the larger target stimulus significantly more than chance in control trials (mean ± SD = 62.35 ± 8.30 %; Wilcoxon-signed rank test, Z = 1.07, p <0.001*). Participants also proved to perceive the Delboeuf illusion as expected, so selecting the stimulus presented in the small context significantly more than chance (mean ± SD = 80.38 ±17.70 %; Z = 1.10, p <0.001*).

Correlation between numerical and continuous quantity discrimination

Considering only those control trials in which the Delboeuf illusion has no effect, we found a significant correlation between performance in the two discriminations (Pearson correlation; $r_{66} = 0.34$, $p = 0.005$). Even considering only those trials in which the illusion has an effect, we found a significant correlation between performance in the two discriminations (Pearson correlation; $r_{66}= 0.31$, $p = 0.002$). The first correlation suggests that those participants who have a higher discrimination ability with continuous quantities also better discriminates between different numerosities. The second correlation instead suggests that those participants who are more influenced by the Delboeuf illusion when it is resembled with a continuous quantity, are also more influenced by it when it is resembled with numerosity arrays.

3.2.Neural level: 7 Hz and 18 Hz tACS stimulations

Numerical discrimination

In the 7 Hz. tACS stimulation, individual analyses revealed that 17 out of 34 participants selected the larger numerosity significantly more than chance in control trials (Appendix D: Table S1). Considering the Delboeuf illusory trials, 12 out of 34 participants selected the numerosity presented in the small context significantly more than chance whereas, interestingly, 4 selected more than chance the one presented in the large context (Appendix D: Table S1). Group analyses revealed that, in the 7 Hz. tACS stimulation, participants selected the larger numerosity significantly more than chance in control trials (mean ± SD = 58.88 ± 8.58 %; one-sample *t-test*, $t_{33} = 6.21$, p <0.001*). Overall, participants proved to perceive the numerical Delboeuf illusion, so selecting the numerosity presented in the small context significantly more than chance (mean ± SD = 57.88 ± 18.88 %; $t_{33} = 2.43$, $p = 0.021$*).

In the 18 Hz. tACS stimulation, individual analyses revealed that 18 out of 34 participants selected the larger numerosity significantly more than chance in control trials (Appendix D: Table S1). Considering the Delboeuf illusory trials, 10 out of 34 participants selected the numerosity presented in the small context significantly more than chance whereas, interestingly, 4 selected more than chance the one presented in the large context (Appendix D: Table S1).

Group analyses revealed that, in the 18 Hz. tACS stimulation, participants selected the larger numerosity significantly more than chance in control trials (mean ± SD = 59.59 ± 8.69 %; one-sample *t-test*, $t_{33} = 6.289$, $p < 0.001$*). Overall, participants did not perceive the numerical Delboeuf illusion, since they did not select any numerosity significantly more than chance (mean ± SD = 55.55 ± 16.59 %; $t_{33} = 1.951$, $p = 0.060$).

Considering the GLMM, it was not observed a statistically significant effect of the stimulation on the participants' accuracy ($\chi^2_2 = 4.11$, $p = 0.128$). On the other hand, a statistically significant effect of the trial type emerged ($\chi^2_4 = 248.58$, $p < 0.001$). In detail, participants reported a significantly lower accuracy in congruent trials, compared to the other trial type (all $p < 0.001$). In the case of incongruent trials, the accuracy was significantly higher, compared to the other trial type (all $p < 0.05$). In the case of large trials, the accuracy was higher, especially when compared to both small ($p < 0.001$) and illusory trials ($p < 0.001$). With small trials, the accuracy tended to be lower, compared to illusory trials ($p < .001$). The complete list of these post-hoc comparisons, including ORs, their 95% CI, z-values, SE, and p-values can be found in Appendix E: Table S2). Lastly, considering the interaction between the stimulation and the trial type, no statistically significant effect was found ($\chi^2_8 = 9.16$, $p = 0.329$).

Continuous quantity discrimination

In the 7 Hz. stimulation, individual analyses revealed that 26 out of 34 participants selected the larger target stimulus significantly more than chance in control trials (Appendix D: Table S1). Considering the Delboeuf illusory trials, 29 out of 34 participants selected the stimulus presented in the small context significantly more than chance (Appendix D: Table S1). Group analyses revealed that, in the 7 Hz. tACS stimulation, participants selected the larger target stimulus significantly more than chance in control trials (mean ± SD = 61.58 ± 7.40 %. Wilcoxon-signed rank test, Z = 1.08, p <0.001*). Participants also proved to perceive the Delboeuf illusion, so selecting the stimulus presented in the small context significantly more than chance (mean ± SD = 78.81 ± 18.44 %; Z = 1.07, *p* <0.001*).

In the 18 Hz. tACS stimulation, individual analyses revealed that 28 out of 34 participants selected the larger target stimulus significantly more than chance in control trials (Appendix D: Table S1). Considering the Delboeuf illusory trials, 29 out of 34 participants selected the stimulus presented in the small context significantly more than chance (Appendix D: Table S1).

Group analyses revealed that, in the 18 Hz. tACS stimulation, participants selected the larger target stimulus significantly more than chance in control trials (mean ± SD = 63.00 ± 6.98 %; Z = 1.159, *p* <0.001*). Participants also proved to perceive the Delboeuf illusion, so selecting the stimulus presented in the small context significantly more than chance (mean ± SD = 82.05 ± 17.93 %; Z = 1.097, *p* <0.001*).

Considering the GLMM, a statistically significant effect of the stimulation on the participants' accuracy was found ($\chi^2{}_2 = 9.52$, $p = 0.009$): participants were more likely to correctly respond in the case of the 18 Hz. tACS stimulation, compared to the 7 Hz. tACS stimulation ($p < 0.01$); comparing both 18 Hz. and 7 Hz. tACS stimulations with the sham condition, no differences in accuracy emerged ($p > 0.05$). Concerning the trial type, a statistically significant effect emerged ($\chi^2_4 = 4437.38$, $p < 0.001$). In detail, compared to all the other trials, the accuracy on congruent trials was lower (all $p < 0.001$), as also found for the numerical discrimination. With incongruent trials, the accuracy was higher (all $p < 0.001$), compared to all the other trial types as also found for the numerical discrimination. The performances in both large and small trials were not significantly different ($p = 0.273$). Instead, in illusory trials, the accuracy was significantly higher, compared to both large ($p < 0.001$) and small trials ($p < 0.001$). The complete list of these post-hoc comparisons, including ORs, their 95% CI, *z*-values, SE, and *p*-values can be found in Appendix E: Table S2). Lastly, considering the interaction between the stimulation and the trial type, no statistically significant effect was found ($\chi^2_8 = 5.78$, $p = 0.672$).

Comparison between numerical and continuous quantity discrimination

In the overall model, the effect of the discrimination emerged as statistically significant ($\chi^2_1 = 443.75$, $p < 0.001$). In particular, participants were significantly more accurate in the continuous quantity discrimination than the numerical one ($p < 0.001$). Furthermore, a statistically significant effect of the stimulation was observed ($\chi^2_2 = 8.79$, $p = 0.012$): participants were less likely to respond correctly in the case of the 7 Hz. tACS stimulation both compared to the 18 Hz. tACS stimulation ($p = 0.019$) and to the sham condition ($p = 0.028$). No difference in accuracy was found between the 18 Hz. tACS stimulation and the sham condition ($p = 0.698$). Considering the interaction between discrimination and stimulation, no statistically significant effect was found ($\chi^2_2 = 5.56$, $p = 0.062$).

Considering the trial type, a statistically significant effect was observed ($\chi^2_4 = 3352.26$, $p < 0.001$). As for the previous models, the accuracy on congruent trials was lower, compared to all the other types of trials (all $p < 0.001$). On the other hand, in incongruent trials, the accuracy was higher compared to all the other trial types (all $p < 0.001$). Instead in the large trials, participants were more likely to respond correctly compared to small trials (*p* <0.001). In illusory trials, the accuracy was higher, compared to both large (*p* <0.001) and small trials (*p* <0.001).

The interaction between the discrimination and the trial type emerged as statistically significant ($\chi^2_4 = 1930.38$, *p* <0.001). In the continuous quantity discrimination, all the previous differences among trial types were found. The only exception concerned the difference in accuracy between large and small trials, which emerged to be no longer statistically significant (*p* = 0.277, Figure 5). In the numerical discrimination, the direction of some differences changed: contrary to the results of the trial type main effect, in the case of large trials, participants were more likely to respond correctly compared to both small (*p* <0.001) and illusory trials (*p* <0.001); finally, in the case of small trials, participants were more likely to respond correctly compared to illusory trials (*p* <0.001). All the other comparisons were statistically significant and coherent with the previous main effects (see Appendix E: Table S2). No further statistically significant effects emerged (all *p* > 0.05).

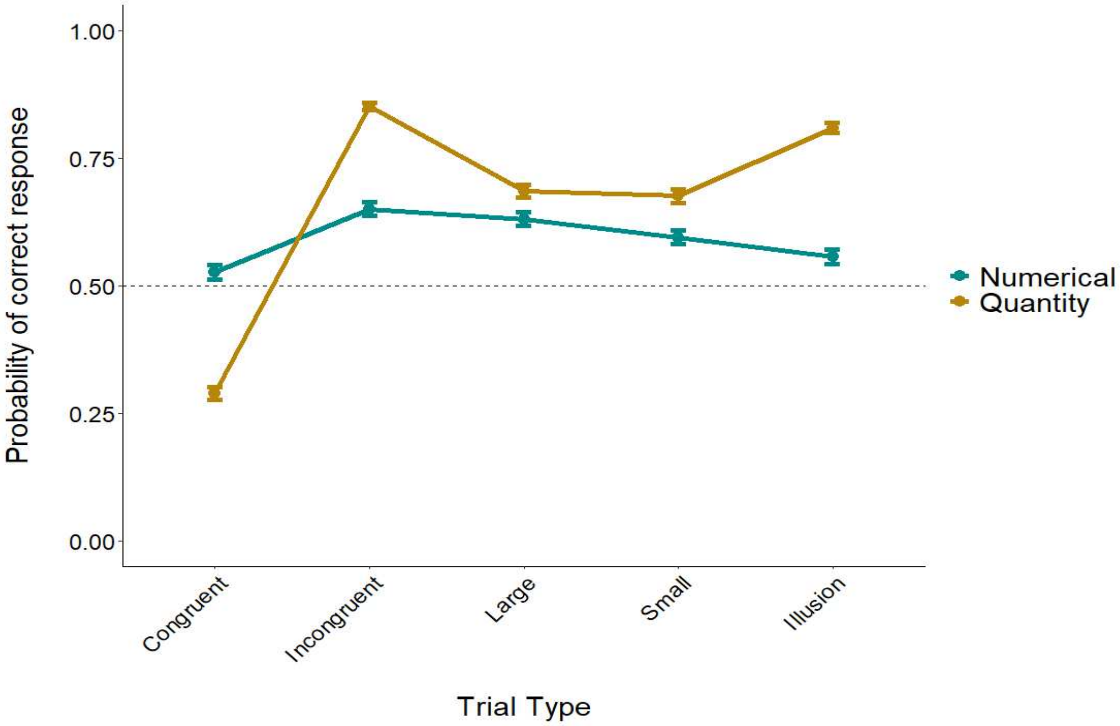

Figure 5. Comparison of the performances (mean ± SE) in the two discrimination tasks in all five types of trials.

4. Discussion

The question of whether human spatial and numerical abilities are processed by the same neuro-cognitive system is widely discussed. This study explored the potential existence of a generalized magnitude system by assessing whether perceptual biases influence both spatial and numerical judgments in the classical and numerical Delboeuf illusions. Through the application of transcranial alternating current stimulation (tACS) at different frequencies (7 Hz, 18 Hz, and placebo), we aimed to uncover how neural oscillations might modulate these perceptual processes, thereby providing insights into the cognitive and neural mechanisms underlying quantity perception.

The results revealed significant differences in participants' ability to discriminate between different quantities, with a notably higher discrimination ability observed for spatial areas compared to numerical quantities. This finding is consistent with existing literature, which suggests that spatial discrimination may be more robust than numerical discrimination due to the differing cognitive processes involved (e.g. Hubbard et al. 2005; Leibovich&Henik, 2014; Lucon-Xiccato, Petrazzini, Agrillo&Bisazza, 2015). Spatial discrimination relies heavily on visual processing pathways that are well-established and perhaps more efficient, whereas numerical discrimination may involve more complex, abstract cognitive functions. Additionally, conflicting evidence exists in the literature regarding the extent of the relationship between continuous and discrete quantity processing. Some studies have reported weak or non-significant correlations between performance in these tasks (e.g. Droit-Volet, Clement&Fayol, 2008; Dormal, Andres&Pesenti, 2008; Cappelletti, Chamberlain, Freeman, Kanai, Butterworht, Price&Rees, 2014), suggesting that the association between continuous and discrete quantity processing may vary across individuals or experimental conditions.

Analysis identified two significant correlations that provide additional insight into the observed discrepancy. The first correlation demonstrates a positive relationship between participants' abilities to discriminate continuous quantities and their ability to distinguish different numerosities, aligning with findings from previous research (Burr&Ross, 2008; Gebius&Reynvoet, 2012). The second correlation reveals a link between participants' susceptibility to the Delboeuf illusion in the context of continuous quantities and their susceptibility to the same illusion when dealing with numerosity arrays. This connection emphasizes the impact of perceptual biases on numerical judgments. Interestingly, while participants generally perceived the classical Delboeuf illusion significantly, our initial statistical analyses did not show a similar effect for numerical stimuli, which could challenge the hypothesis of a unified perceptual mechanism for both types of quantities. However, further analysis revealed a significant correlation, indicating a shared perceptual foundation after all.

Contrary to our initial hypothesis, tACS at 7 Hz. did not enhance the strength of the perceptual illusion. Instead, it appeared to diminish the illusion's strength. This unexpected result indicates that theta-frequency stimulation might have a different effect on visual integration than previously thought. It was initially hypothesized that theta-frequency tACS would increase visual integration and thereby strengthen the illusion, based on previous studies suggesting that theta oscillations are associated with holistic processing. However, our findings suggest a more nuanced interaction between neural oscillations and perceptual processes, which may vary depending on the specific nature of the task and the type of visual input.

These results contribute significantly to our understanding of the cognitive processes involved in quantity perception. They highlight the potential of non-invasive brain stimulation techniques, such as tACS, in modulating visual perception. The observed correlation between different types of magnitude processing implies that interventions targeting these perceptual biases could have broad applications across various cognitive domains, potentially benefiting fields such as education, where enhanced numerical and spatial reasoning skills are crucial.

Moreover, our findings open up several avenues for future research. One important direction would be to investigate the precise neural mechanisms by which different tACS frequencies influence perceptual biases. This could involve using more advanced neuroimaging techniques to directly observe changes in brain activity associated with tACS. Another promising area of research would be to explore whether similar effects of tACS can be observed in other types of illusions or cognitive tasks. Such studies could help to generalize our findings and further elucidate the relationship between neural oscillations and cognitive functions.

This study also only explored the effects of two specific tACS frequencies (7 Hz. and 18 Hz.), without examining the full spectrum of possible frequencies. Different frequencies might have varying effects on perceptual and cognitive processes. Investigating a wider range of frequencies in future research could help determine the optimal parameters for modulating magnitude processing.

Additionally, expanding the sample size and including a more diverse participant pool could help to generalize the findings and provide more robust evidence for the existence of a generalized magnitude system. Factors such as age, gender, and cultural background may influence magnitude processing, and understanding these influences could lead to more tailored and effective interventions.

In conclusion, this study provides valuable insights into the neural and cognitive mechanisms underlying magnitude processing. It suggests that a generalized magnitude system may exist and that tACS can modulate visual perception in complex ways. These findings not only enhance our theoretical understanding of perception but also have practical implications for developing new methods to improve cognitive functions through non-invasive brain stimulation techniques. As we continue to unravel the intricacies of human perception, such research holds promise for advancing both scientific knowledge and practical applications in various fields.

5. Conclussion

This study provides evidence for a shared cognitive mechanism underlying the perception of spatial and numerical magnitudes, as demonstrated by the correlation between continuous quantity and numerical discrimination tasks. Continuous quantity discrimination was consistently more accurate than numerical discrimination, highlighting a cognitive advantage for processing spatial information. The application of 7 Hz tACS reduced discrimination accuracy but enhanced illusion perception, contrary to our initial hypothesis. In contrast, 18 Hz tACS maintained accuracy and diminished illusion strength, suggesting frequency-specific modulation of perceptual processes. These findings contribute to our understanding of quantity perception and underscore the potential of tACS in exploring neural processes of visual perception. Future research should further investigate the neural processes and methodological factors affecting numerical discrimination tasks.

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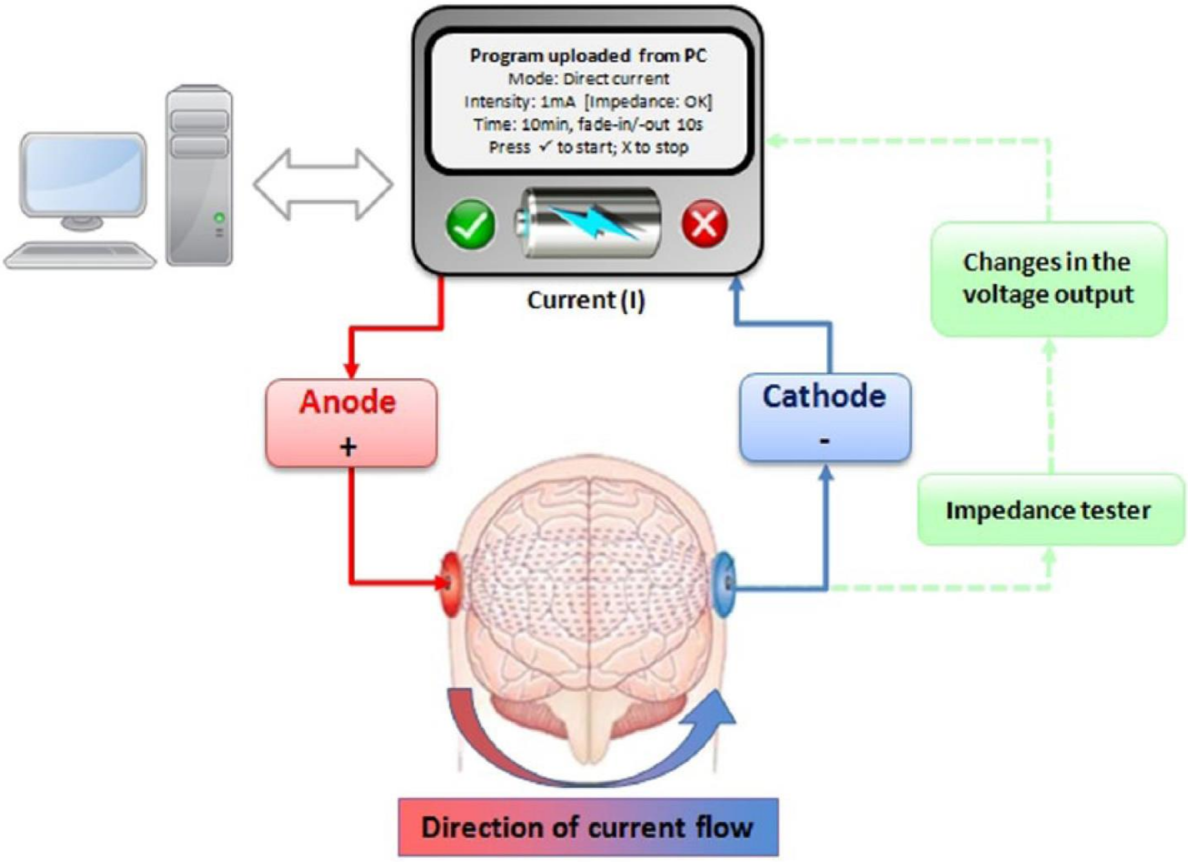
7. Appendix: supplementary material

Appendix A

Schematization of the transcranial electrical stimulation (tES) stimulating device (Fertonani&Miniussi, 2017)



Appendix B

Before undergoing Transcranial Magnetic Stimulation (TMS) or Transcranial Electrical Stimulation (tES) please read and answer the following questions. The information you provide is strictly confidential and is used to minimize risk factors when using these techniques

Do you suffer or have you ever suffered from seizures, febrile convulsions, or recurrent faintings?	**YES**	**NO**
Do you have a family history of epilepsy? If YES please indicate the degree of relatedness of the family member(s)	**YES**	**NO**
Have you ever suffered a traumatic brain injury? If Yes please provide details below.	**YES**	**NO**
Do you have metal inserts in your skull (surgical clips "in your head")?	**YES**	**NO**
Do you have any heart conditions?	**YES**	**NO**
Do you have a pacemaker in your heart?	**YES**	**NO**
Do you take tricyclic antidepressants?	**YES**	**NO**
Do you take neuroleptic medications?	**YES**	**NO**
Do you suffer from severe and frequent headaches?	**YES**	**NO**
Have you had more than three units of alcohol in the past 24 hours?	**YES**	**NO**
Have you had more than 2 cups of coffee or caffeine from other sources in the last 2 hours?	**YES**	**NO**
Have you used any drugs in the last 24 hours? If YES please indicate which	**YES**	**NO**
Have you participated in other experiments with tRNS before?	**YES**	**NO**
Are you right-handed or left-handed?	**R**	**L**
Women only:		
Are you in a definite or presumed state of pregnancy?	**YES**	**NO**

Date of birth ____________________ Signature___________________________

Appendix C

Subject Code: ____
Date: __/__/______
Experiment:

Did you experience any uncomfortable sensations during electrical stimulation?

Answer the following questions regarding the different sensations you experienced, indicating the degree of intensity according to the following scale:

No = I have not experienced the described sensation (0)
Mild = I slightly felt the described sensation (1)
Moderate = I felt the described sensation (2)
Discreet = I have discreetly perceived the described sensation (3)
Strong = I strongly felt the described sensation (4)

During stimulation:

Pinch	No	Mild	Moderate	Discreet	Strong
Pain	No	Mild	Moderate	Discreet	Strong
Burning	No	Mild	Moderate	Discreet	Strong
Heat	No	Mild	Moderate	Discreet	Strong
Pressure	No	Mild	Moderate	Discreet	Strong
Metallic/Ferrous taste in mouth	No	Mild	Moderate	Discreet	Strong
Fatigue	No	Mild	Moderate	Discreet	Strong
Other _______________	No	Mild	Moderate	Discreet	Strong

When did the sensation first begin?

At the onset of stimulation
In the middle of stimulation
Towards the end of stimulation

How long did it last?

A short time
Half stimulation
Whole stimulation

How much did this sensation influence the task?

It did not affect
A bit
Moderately
Discreetly
A lot

Specify whether these sensations were located on the head or in other areas:

On the head______________________
In other areas______________________

Do you think you received real stimulation or placebo stimulation?

Real
Placebo
I don't know

Participant's signature____
Experimenter's signature____

Appendix D

Table S1. Humans' individual and group performance (small, large, congruent, incongruent trials: frequency of choices for the larger numerosity and area; Delboeuf illusion: frequency of choices for the expected larger numerosity, i.e., presented in the small background). Statistics were calculated with binomial tests for individual analyses and with one-sample *t* tests or Wilcoxon-signed rank tests for group analyses. Asterisks (*) denote a significant departure from chance level (0.5).

			Continuous quantity discrimination					**Numerical discrimination**					
Subject	**Age**	**Gender**	**Small**	**Large**	**Congruent**	**Incongruent**	**Delboeuf illusion**	**Small**	**Large**	**Congruent**	**Incongruent**	**Delboeuf illusion**	**tACs**
1	24	F	50/60 $p<0.001$*	56/60 $p<0.001$*	1/59 $p<0.001$*	60/60 $p<0.001$*	60/60 $p<0.001$*	54/59 $p<0.001$*	53/60 $p<0.001$*	49/60 $p<0.001$*	58/60 $p<0.001$*	40/60 $p=0.013$*	Sham
			51/59 $p<0.001$*	55/60 $p<0.001$*	1/59 $p<0.001$*	60/60 $p<0.001$*	60/60 $p<0.001$*	46/56 $p<0.001$*	51/60 $p<0.001$*	46/58 $p<0.001$*	53/60 $p<0.001$*	43/60 $p=0.001$*	7 Hz
			48/60 $p<0.001$*	48/57 $p<0.001$*	4/60 $p<0.001$*	60/60 $p<0.001$*	60/60 $p<0.001$*	46/59 $p<0.001$*	48/57 $p<0.001$*	45/60 $p<0.001$*	51/58 $p<0.001$*	30/59 $p=1.000$	18 Hz
2	30	M	37/58 $p=0.048$*	41/60 $p=0.006$*	7/60 $p<0.001$*	59/60 $p<0.001$*	59/60 $p<0.001$*	37/54 $p=0.009$*	33/52 $p=0.070$	13/54 $p<0.001$*	49/55 $p<0.001$*	39/53 $p<0.001$*	Sham
			18/28 $p=0.185$	24/37 $p=0.099$	12/41 $p=0.012$*	30/32 $p<0.001$*	28/31 $p<0.001$*	37/54 $p=0.009$*	40/52 $p<0.001$*	33/56 $p=0.229$	40/54 $p<0.001$*	30/52 $p=0.332$	7 Hz
			48/58 $p<0.001$*	38/58 $p=0.025$*	12/59 $p<0.001$*	58/60 $p<0.001$*	55/59 $p<0.001$*	42/57 $p<0.001$*	35/59 $p=0.193$	24/57 $p=0.289$	48/57 $p<0.001$*	37/55 $p=0.015$*	18 Hz
3	22	F	45/59 $p<0.001$*	49/59 $p<0.001$*	10/58 $p<0.001$*	56/58 $p<0.001$*	52/58 $p<0.001$*	32/58 $p=0.512$	30/55 $p=0.590$	8/57 $p<0.001$*	49/55 $p<0.001$*	36/59 $p=0.117$	Sham
			44/57	39/48	8/57	53/56	52/56	34/55	38/55	17/55	47/57	41/57	7 Hz

			$p<0.001$*	$p<0.001$*	$p<0.001$*	$p<0.001$*	$p<0.001$*	$p=0.105$	$p=0.006$*	$p=0.006$*	$p<0.001$*	$p=0.001$*	
			34/49 $p=0.009$*	34/42 $p<0.001$*	14/55 $p<0.001$*	54/55 $p<0.001$*	40/49 $p<0.001$*	32/51 $p=0.092$	23/40 $p=0.430$	14/51 $p=0.001$*	39/43 $p<0.001$*	32/43 $p=0.002$*	18 Hz
4	22	F	31/60 $p=0.897$	32/59 $p=0.603$	16/58 $p<0.001$*	45/60 $p<0.001$*	43/59 $p<0.001$*	29/60 $p=0.897$	37/59 $p=0.067$	31/59 $p=0.795$	32/60 $p=0.699$	32/60 $p=0.699$	Sham
			35/59 $p=0.193$	33/60 $p=0.519$	16/59 $p<0.001$*	52/60 $p<0.001$*	49/60 $p<0.001$*	31/60 $p=0.897$	31/60 $p=0.897$	46/60 $p<0.001$*	17/60 $p=0.001$*	17/60 $p=0.001$*	7 Hz
			34/59 $p=0.298$	36/60 $p=0.155$*	25/60 $p=0.245$	49/58 $p<0.001$*	47/59 $p<0.001$*	28/60 $p=0.699$	38/60 $p=0.052$	41/59 $p=0.004$*	23/60 $p=0.092$	21/60 $p=0.027$*	18 Hz
5	24	M	31/59 $p=0.795$	31/60 $p=0.897$	31/60 $p=0.897$	37/60 $p=0.092$	33/59 $p=0.435$	35/59 $p=0.193$	43/59 $p=0.001$*	29/58 $p=1.000$	37/59 $p=0.067$	28/60 $p=0.699$	Sham
			27/58 $p=0.694$	31/58 $p=0.694$	28/59 $p=0.795$	26/58 $p=0.512$	28/59 $p=0.795$	33/57 $p=0.289$	27/60 $p=0.519$	31/60 $p=0.897$	32/59 $p=0.603$	34/58 $p=0.237$	7 Hz
			31/60 $p=0.897$	29/56 $p=0.894$	34/58 $p=0.237$	34/58 $p=0.237$	27/53 $p=1.000$	36/58 $p=0.087$	37/56 $p=0.022$*	26/58 $p=0.512$	39/57 $p=0.008$*	30/56 $p=0.689$	18 Hz
6	23	F	36/60 $p=0.155$	30/55 $p=0.590$	17/56 $p=0.005$*	41/60 $p=0.006$*	37/57 $p=0.033$*	35/58 $p=0.148$	31/58 $p=0.694$	33/57 $p=0.289$	38/58 $p=0.025$*	29/57 $p=1.000$	Sham
			35/58 $p=0.148$	34/60 $p=0.366$	27/59 $p=0.603$	39/60 $p=0.027$*	41/59 $p=0.004$*	33/59 $p=0.559$	31/59 $p=0.795$	36/59 $p=0.117$	27/59 $p=0.603$	29/60 $p=0.897$	7 Hz
			31/60 $p=0.897$	39/58 $p=0.012$*	26/56 $p=0.689$	46/57 $p<0.001$*	42/59 $p=0.002$*	38/60 $p=0.052$	37/59 $p=0.067$	27/59 $p=0.603$	30/60 $p=1.000$	34/60 $p=0.366$	18 Hz
7	24	F	36/57 $p=0.063$	39/58 $p=0.012$*	21/59 $p=0.036$*	56/59 $p<0.001$*	51/59 $p<0.001$*	47/60 $p<0.001$*	53/60 $p<0.001$*	51/59 $p<0.001$*	43/60 $p=0.001$*	19/60 $p<0.001$*	Sham
			45/58 $p<0.001$*	36/51 $p=0.005$*	27/54 $p=1.000$	54/56 $p<0.001$*	42/52 $p<0.001$*	48/58 $p<0.001$*	43/58 $p<0.001$*	54/59 $p<0.001$*	24/60 $p=0.155$	14/59 $p<0.001$*	7 Hz

			44/59 $p<0.001$*	34/58 $p=0.237$	26/59 $p=0.435$	56/60 $p<0.001$*	51/60 $p<0.001$*	50/59 $p<0.001$*	48/59 $p<0.001$*	59/60 $p<0.001$*	35/60 $p=0.245$	16/59 $p<0.001$*	18 Hz
8	22	F	50/59 $p<0.001$*	51/60 $p<0.001$*	22/60 $p=0.052$	57/60 $p<0.001$*	56/60 $p<0.001$*	34/60 $p=0.366$	39/59 $p=0.018$*	22/60 $p=0.052$	40/60 $p=0.013$*	29/60 $p=0.897$	Sham
			37/60 $p=0.092$	36/60 $p=0.115$	23/60 $p=0.092$	44/59 $p<0.001$*	41/57 $p=0.001$*	38/58 $p=0.025$*	43/60 $p=0.001$*	25/60 $p=0.245$	55/60 $p<0.001$*	41/59 $p=0.004$*	7 Hz
			45/60 $p<0.001$*	42/60 $p=0.003$*	30/60 $p=1.000$	52/60 $p<0.001$*	40/60 $p=0.013$*	40/60 $p=0.013$*	50/60 $p<0.001$*	20/60 $p=0.013$*	56/60 $p<0.001$*	48/60 $p<0.001$*	18 Hz
9	25	F	43/60 $p<0.001$*	40/59 $p=0.009$*	22/60 $p=0.052$	53/60 $p<0.001$*	47/60 $p<0.001$*	37/60 $p=0.092$	30/59 $p=1.000$	47/59 $p<0.001$*	37/59 $p=0.067$	32/59 $p=0.603$	Sham
			30/59 $p=1.000$	29/59 $p=1.000$	7/60 $p<0.001$*	54/58 $p<0.001$*	49/60 $p<0.001$*	33/60 $p=0.519$	35/60 $p=0.245$	25/60 $p=0.245$	34/60 $p=0.366$	41/60 $p=0.006$*	7 Hz
			46/59 $p<0.001$*	43/60 $p=0.001$*	9/60 $p<0.001$*	58/59 $p<0.001$*	54/60 $p<0.001$*	33/60 $p=0.519$	40/60 $p=0.013$*	48/60 $p<0.001$*	43/60 $p=0.001$*	37/60 $p=0.092$	18 Hz
10	24	F	35/60 $p=0.245$	33/59 $p=0.435$	19/60 $p=0.006$*	37/60 $p=0.092$	46/60 $p<0.001$*	31/60 $p=0.897$	35/59 $p=0.193$	17/59 $p=0.002$*	46/60 $p<0.001$*	41/60 $p=0.006$*	Sham
			38/60 $p=0.052$	39/59 $p=0.018$*	13/60 $p<0.001$*	55/59 $p<0.001$*	52/58 $p<0.001$*	33/60 $p=0.519$	35/60 $p=0.245$	18/60 $p=0.003$*	50/59 $p<0.001$*	51/60 $p<0.001$*	7 Hz
			44/60 $p<0.001$*	39/60 $p=0.027$*	20/60 $p=0.013$*	45/60 $p<0.001$*	48/59 $p<0.001$*	38/60 $p=0.052$	33/60 $p=0.519$	26/59 $p=0.435$	43/59 $p=0.001$*	38/59 $p=0.036$*	18 Hz
11	24	F	29/58 $p=1.000$	33/58 $p=0.358$	33/57 $p=0.289$	29/59 $p=1.000$	26/59 $p=0.435$	37/60 $p=0.092$	42/59 $p=0.002$*	40/59 $p=0.009$*	16/60 $p<0.001$*	24/60 $p=0.155$	Sham
			38/60 $p=0.052$	37/58 $p=0.048$*	43/57 $p<0.001$*	28/58 $p=0.896$	52/58 $p<0.001$*	32/60 $p=0.699$	38/60 $p=0.052$	53/59 $p<0.001$*	21/60 $p=0.027$*	24/60 $p=0.155$	7 Hz
			26/59 $p=0.435$	33/59 $p=0.435$	31/58 $p=0.694$	30/59 $p=1.000$	33/59 $p=0.435$	27/56 $p=0.894$	30/58 $p=0.896$	34/60 $p=0.366$	24/56 $p=0.350$	27/58 $p=0.694$	18 Hz

12	23	M	43/58 $p<0.001$*	36/54 $p=0.020$*	44/54 $p<0.001$*	41/57 $p=0.001$*	25/57 $p=0.427$	30/58 $p=0.896$	40/59 $p=0.009$*	49/60 $p<0.001$*	20/59 $p=0.018$*	19/57 $p=0.016$*	Sham
			40/59 $p=0.009$*	42/60 $p=0.003$*	51/60 $p<0.001$*	31/60 $p=0.897$	19/58 $p=0.012$*	33/60 $p=0.519$	45/59 $p<0.001$*	53/59 $p<0.001$*	13/59 $p<0.001$*	11/60 $p<0.001$*	7 Hz
			39/59 $p=0.018$*	47/58 $p<0.001$*	52/58 $p<0.001$*	23/59 $p=0.117$	15/60 $p<0.001$*	42/60 $p=0.003$*	47/60 $p<0.001$*	9/60 $p<0.001$*	54/59 $p<0.001$*	11/60 $p<0.001$*	18 Hz
13	22	F	51/60 $p<0.001$*	50/60 $p<0.001$*	0/60 $p<0.001$*	59/59 $p=0.001$*	60/60 $p=0.427$	28/60 $p=0.699$	33/60 $p=0.519$	5/60 $p<0.001$*	58/59 $p<0.001$*	54/60 $p<0.001$*	Sham
			39/60 $p=0.027$*	42/60 $p=0.003$*	4/60 $p<0.001$*	59/59 $p<0.001$*	57/60 $p<0.001$*	33/59 $p=0.435$	35/60 $p=0.245$	11/59 $p<0.001$*	50/60 $p<0.001$*	48/60 $p<0.001$*	7 Hz
			47/59 $p<0.001$*	52/59 $p<0.001$*	1/60 $p<0.001$*	59/60 $p<0.001$*	58/59 $p<0.001$*	36/58 $p=0.087$	32/59 $p=0.603$	3/59 $p<0.001$*	57/60 $p<0.001$*	51/59 $p<0.001$*	18 Hz
14	23	F	50/60 $p<0.001$*	44/59 $p<0.001$*	10/60 $p<0.001$*	60/60 $p<0.001$*	56/60 $p<0.001$*	31/60 $p=0.897$	28/59 $p=0.795$	5/60 $p<0.001$*	57/60 $p<0.001$*	47/60 $p<0.001$*	Sham
			44/60 $p<0.001$*	42/58 $p=0.001$*	12/60 $p<0.001$*	53/60 $p<0.001$*	55/59 $p<0.001$*	35/57 $p=0.111$	34/55 $p=0.105$	22/58 $p=0.087$	44/58 $p<0.001$*	39/55 $p=0.003$*	7 Hz
			40/60 $p=0.013$*	48/60 $p<0.001$*	6/59 $p<0.001$*	60/60 $p<0.001$*	56/60 $p<0.001$*	27/60 $p=0.519$	34/59 $p=0.298$	8/60 $p<0.001$*	56/60 $p<0.001$*	51/60 $p<0.001$*	18 Hz
15	23	F	40/59 $p=0.009$*	32/59 $p=0.603$	5/59 $p<0.001$*	58/60 $p<0.001$*	60/60 $p<0.001$*	47/60 $p<0.001$*	48/58 $p<0.001$*	57/58 $p<0.001$*	17/59 $p=0.002$*	13/60 $p<0.001$*	Sham
			43/59 $p=0.001$*	35/57 $p=0.111$	4/59 $p<0.001$*	59/60 $p<0.001$*	57/59 $p<0.001$*	45/59 $p<0.001$*	49/57 $p<0.001$*	54/59 $p<0.001$*	34/59 $p<0.001$*	12/60 $p<0.001$*	7 Hz
			44/58 $p<0.001$*	48/60 $p<0.001$*	6/56 $p<0.001$*	56/59 $p<0.001$*	57/60 $p<0.001$*	38/55 $p=0.006$*	36/56 $p=0.044$*	47/57 $p<0.001$*	25/56 $p=0.504$	21/55 $p=0.105$	18 Hz
16	25	F	44/58 $p<0.001$*	38/49 $p<0.001$*	14/59 $p<0.001$*	59/59 $p<0.001$*	56/60 $p<0.001$*	41/57 $p=0.001$*	47/59 $p<0.001$*	51/60 $p<0.001$*	35/58 $p=0.148$	22/60 $p=0.052$	Sham

			44/58 $p<0.001$*	44/58 $p<0.001$*	9/60 $p<0.001$*	60/60 $p<0.001$*	56/60 $p<0.001$*	39/58 $p=0.012$*	39/60 $p=0.027$*	36/58 $p=0.087$	45/59 $p<0.001$*	30/58 $p=0.896$	7 Hz
			44/60 $p<0.001$*	46/58 $p<0.001$*	5/59 $p<0.001$*	60/60 $p<0.001$*	56/60 $p<0.001$*	48/60 $p<0.001$*	45/57 $p<0.001$*	43/59 $p=0.001$*	39/57 $p=0.008$*	28/59 $p=0.795$	18 Hz
17	24	M	52/56 $p<0.001$*	49/54 $p<0.001$*	22/58 $p=0.087$	56/59 $p<0.001$*	51/58 $p<0.001$*	28/45 $p=0.135$	34/40 $p<0.001$*	37/46 $p<0.001$*	24/41 $p=0.349$	15/37 $p=0.324$	Sham
			53/60 $p<0.001$*	56/59 $p<0.001$*	16/59 $p=0.001$*	60/60 $p<0.001$*	56/60 $p<0.001$*	37/60 $p=0.092$	49/60 $p<0.001$*	49/60 $p<0.001$*	30/60 $p=1.000$	31/59 $p=0.795$	7 Hz
			48/60 $p<0.001$*	48/59 $p<0.001$*	22/59 $p=0.067$	59/59 $p<0.001$*	58/59 $p<0.001$*	35/59 $p=0.193$	38/60 $p=0.052$	45/60 $p<0.001$*	24/60 $p=0.155$	22/60 $p=0.052$	18 Hz
18	35	F	43/60 $p=0.001$*	44/60 $p<0.001$*	28/59 $p=0.795$	50/60 $p<0.001$*	35/60 $p=0.245$	31/60 $p=0.897$	33/60 $p=0.519$	27/60 $p=0.519$	45/60 $p<0.001$*	36/59 $p=0.117$	Sham
			35/60 $p=0.245$	35/60 $p=0.245$	2/60 $p<0.001$*	59/60 $p<0.001$*	57/60 $p<0.001$*	31/60 $p=0.897$	35/60 $p=0.245$	15/60 $p<0.001$*	49/60 $p<0.001$*	52/60 $p<0.001$*	7 Hz
			41/60 $p=0.006$*	34/58 $p=0.237$	11/60 $p<0.001$*	49/59 $p<0.001$*	51/59 $p<0.001$*	38/59 $p=0.036$	31/60 $p=0.897$	12/59 $p<0.001$*	51/60 $p<0.001$*	43/60 $p=0.001$*	18 Hz
19	22	F	32/60 $p=0.699$	33/60 $p=0.519$	20/59 $p=0.018$*	42/57 $p<0.001$*	39/58 $p=0.012$*	32/60 $p=0.699$	33/60 $p=0.519$	28/59 $p=0.795$	42/60 $p=0.003$*	24/59 $p=0.193$	Sham
			32/57 $p=0.427$	19/57 $p=0.016$*	16/59 $p=0.001$*	49/58 $p<0.001$*	41/58 $p=0.002$*	33/59 $p=0.435$	31/59 $p=0.795$	25/58 $p=0.358$	31/59 $p=0.795$	26/58 $p=0.512$	7 Hz
			30/58 $p=0.896$	33/60 $p=0.519$	11/60 $p<0.001$*	44/60 $p<0.001$*	48/60 $p<0.001$*	29/58 $p=1.000$	28/60 $p=0.699$	16/60 $p<0.001$*	41/58 $p=0.002$*	35/59 $p=0.193$	18 Hz
20	24	F	39/60 $p=0.018$*	35/59 $p=0.193$	19/60 $p=0.006$*	53/59 $p<0.001$*	50/60 $p<0.001$*	34/60 $p=0.366$	35/60 $p=0.245$	31/58 $p=0.694$	44/60 $p<0.001$*	31/59 $p=0.897$	Sham
			41/60 $p=0.006$*	48/60 $p<0.001$*	19/59 $p=0.009$*	55/59 $p<0.001$*	50/59 $p<0.001$*	33/60 $p=0.519$	36/59 $p=0.117$	31/59 $p=0.795$	36/60 $p=0.155$	27/57 $p=0.791$	7 Hz

			35/60 $p=0.245$	33/59 $p=0.435$	14/60 $p<0.001$*	54/60 $p<0.001$*	54/60 $p<0.001$*	31/59 $p=0.795$	39/60 $p=0.027$*	37/60 $p=0.092$	32/58 $p=0.512$	26/60 $p=0.366$	18 Hz
21	23	F	29/60 $p=0.897$	38/60 $p=0.052$	19/60 $p=0.006$*	40/59 $p=0.009$*	43/58 $p<0.001$*	32/59 $p=0.603$	35/58 $p=0.148$	31/59 $p=0.795$	35/60 $p=0.245$	38/60 $p=0.052$	Sham
			29/59 $p=1.000$	38/60 $p=0.052$	21/60 $p=0.027$*	47/60 $p<0.001$*	40/59 $p=0.009$*	29/60 $p=0.897$	31/60 $p=0.897$	22/59 $p=0.067$	48/57 $p<0.001$*	37/60 $p=0.092$	7 Hz
			38/60 $p=0.052$	38/59 $p=0.036$*	20/58 $p=0.025$*	54/60 $p<0.001$*	48/60 $p<0.001$*	27/58 $p=0.694$	34/59 $p=0.298$	31/59 $p=0.795$	34/59 $p=0.298$	34/60 $p=0.366$	18 Hz
22	24	F	30/58 $p=0.896$	29/59 $p=1.000$	26/59 $p=0.435$	33/58 $p=0.358$	30/58 $p=0.896$	29/59 $p=1.000$	28/59 $p=0.795$	34/60 $p=0.366$	29/56 $p=0.894$	27/58 $p=0.694$	Sham
			29/59 $p=1.000$	33/60 $p=0.519$	35/58 $p=0.148$	29/58 $p=1.000$	27/60 $p=0.519$	30/58 $p=0.896$	25/59 $p=0.298$	31/57 $p=0.597$	32/58 $p=0.512$	34/59 $p=0.298$	7 Hz
			35/60 $p=0.245$	30/60 $p=1.000$	26/60 $p=0.366$	40/59 $p=0.009$*	34/59 $p=0.298$	32/60 $p=0.699$	36/60 $p=0.155$	32/59 $p=0.603$	32/60 $p=0.699$	26/60 $p=0.366$	18 Hz
23	24	F	44/60 $p<0.001$*	44/59 $p<0.001$*	9/60 $p<0.001$*	59/60 $p<0.001$*	53/60 $p<0.001$*	33/60 $p=0.519$	30/56 $p=0.689$	25/60 $p=0.245$	47/58 $p=0.048$*	34/59 $p=0.298$	Sham
			43/57 $p<0.001$*	39/57 $p=0.008$*	18/60 $p=0.003$*	54/60 $p<0.001$*	51/59 $p<0.001$*	28/58 $p=0.896$	29/60 $p=0.897$	25/58 $p=0.358$	36/60 $p=0.155$	31/58 $p=0.694$	7 Hz
			40/58 $p=0.005$*	48/58 $p<0.001$*	7/58 $p<0.001$*	49/58 $p<0.001$*	52/58 $p<0.001$*	32/59 $p=0.603$	28/58 $p=0.896$	25/59 $p=0.298$	35/60 $p=0.245$	36/58 $p=0.087$	18 Hz
24	22	F	33/60 $p=0.519$	36/59 $p=0.117$	7/60 $p<0.001$*	54/59 $p<0.001$*	52/59 $p<0.001$*	29/60 $p=0.897$	28/60 $p=0.699$	26/60 $p=0.366$	39/59 $p=0.018$*	39/58 $p=0.012$*	Sham
			34/57 $p=0.185$	41/56 $p=0.001$*	7/60 $p<0.001$*	58/60 $p<0.001$*	50/60 $p<0.001$*	28/60 $p=0.699$	25/59 $p=0.298$	27/59 $p=0.603$	35/59 $p=0.193$	32/58 $p=0.512$	7 Hz
			32/60 $p=0.699$	24/55 $p=0.419$	32/57 $p=0.427$	33/58 $p=0.358$	26/56 $p=0.689$	29/59 $p=1.000$	33/58 $p=0.358$	40/60 $p=0.013$*	18/56 $p=0.010$*	22/60 $p=0.087$	18 Hz

25	22	F	26/59 p=0.435	28/60 p=0.699	24/60 p=0.155	34/60 p=0.366	34/60 p=0.366	30/60 p=1.000	22/59 p=0.067	29/59 p=1.000	29/59 p=1.000	33/59 p=0.435	Sham
			37/60 p=0.092	22/59 p=0.067	29/60 p=0.897	39/59 p=0.018*	35/59 p=0.193	29/60 p=0.897	25/60 p=0.245	28/59 p=0.795	32/60 p=0.699	31/60 p=0.897	7 Hz
			27/60 p=0.519	26/59 p=0.435	18/60 p=0.003*	35/60 p=0.245	36/59 p=0.117	30/60 p=1.000	28/60 p=0.699	31/59 p=0.795	30/60 p=1.000	30/60 p=1.000	18 Hz
26	21	M	41/56 p=0.001*	51/60 p<0.001*	11/59 p<0.001*	59/60 p<0.001*	58/59 p<0.001*	34/59 p=0.298	47/59 p<0.001*	50/57 p<0.001*	37/60 p=0.092	21/59 p=0.036*	Sham
			40/49 p<0.001*	48/56 p<0.001*	11/56 p<0.001*	54/54 p<0.001*	52/54 p<0.001*	35/59 p=0.193	51/59 p<0.001*	42/59 p=0.002*	34/60 p=0.366	28/59 p=0.795	7 Hz
			38/53 p=0.002*	49/57 p<0.001*	11/52 p<0.001*	56/57 p<0.001*	57/59 p<0.001*	37/56 p=0.022*	39/55 p=0.003*	33/54 p=0.134	31/52 p=0.212	26/50 p=0.888	18 Hz
27	29	F	32/60 p=0.699	32/58 p=0.512	25/60 p=0.245	29/60 p=0.897	28/60 p=0.699	34/59 p=0.298	36/60 p=0.155	33/60 p=0.519	34/60 p=0.366	31/59 p=0.795	Sham
			39/59 p=0.018*	37/57 p=0.033*	12/57 p<0.001*	49/60 p<0.001*	39/60 p=0.027*	35/60 p=0.245	36/60 p=0.155	19/59 p=0.009*	39/60 p=0.027*	36/60 p=0.155	7 Hz
			46/59 p<0.001*	34/59 p=0.298	8/60 p<0.001*	57/60 p<0.001*	54/57 p<0.001*	42/59 p=0.002*	40/60 p=0.013*	22/59 p=0.067	46/59 p<0.001*	36/59 p=0.117	18 Hz
28	22	F	42/58 p=0.001*	41/58 p=0.002*	14/58 p<0.001*	53/57 p<0.001*	55/59 p<0.001*	31/58 p=0.694	40/58 p=0.005*	41/57 p=0.001*	28/59 p=0.795	26/57 p=0.597	Sham
			25/60 p=0.245	32/58 p=0.512	26/59 p=0.435	29/60 p=0.897	24/60 p=0.155	21/59 p=0.036*	28/59 p=0.795	28/60 p=0.699	39/59 p=0.018*	32/59 p=0.603	7 Hz
			43/60 p=0.001*	45/60 p<0.001*	10/60 p<0.001*	58/60 p<0.001*	57/60 p<0.001*	29/60 p=0.897	30/60 p=1.000	34/60 p=0.366	36/59 p=0.117	36/60 p=0.155	18 Hz
29	24	F	40/60 p=0.013*	40/60 p=0.013*	28/60 p=0.699	49/60 p<0.001*	51/60 p<0.001*	35/59 p=0.193	47/60 p<0.001*	32/60 p=0.699	43/60 p=0.001*	37/60 p=0.092	Sham

			50/60 $p<0.001$*	46/60 $p<0.001$*	11/60 $p<0.001$*	58/60 $p<0.001$*	58/60 $p<0.001$*	33/59 $p=0.435$	34/57 $p=0.185$	18/57 $p=0.008$*	42/59 $p=0.002$*	32/59 $p=0.603$	7 Hz
			48/60 $p<0.001$*	43/60 $p=0.001$*	24/60 $p=0.155$	54/60 $p<0.001$*	49/60 $p<0.001$*	27/59 $p=0.603$	30/58 $p=0.896$	27/58 $p=0.694$	38/58 $p=0.358$	32/59 $p=0.603$	18 Hz
30	24	F	53/60 $p<0.001$*	46/60 $p<0.001$*	16/60 $p<0.001$*	54/58 $p<0.001$*	57/60 $p<0.001$*	39/60 $p=0.027$*	38/60 $p=0.052$	43/59 $p=0.001$*	29/60 $p=0.897$	19/60 $p=0.006$*	Sham
			49/60 $p<0.001$*	42/60 $p=0.003$*	10/60 $p<0.001$*	59/60 $p<0.001$*	56/60 $p<0.001$*	33/59 $p=0.435$	40/59 $p=0.009$*	40/58 $p=0.005$*	22/59 $p=0.067$	27/57 $p=0.791$	7 Hz
			45/60 $p<0.001$*	43/60 $p=0.001$*	8/60 $p<0.001$*	59/60 $p<0.001$*	60/60 $p<0.001$*	30/60 $p=1.000$	24/60 $p=0.155$	14/60 $p<0.001$*	47/60 $p<0.001$*	40/60 $p=0.013$*	18 Hz
31	23	F	40/60 $p=0.013$*	47/59 $p<0.001$*	9/60 $p<0.001$*	56/60 $p<0.001$*	55/60 $p<0.001$*	42/60 $p=0.003$*	38/59 $p=0.036$*	16/60 $p<0.001$*	56/60 $p<0.001$*	45/58 $p<0.001$*	Sham
			27/54 $p=1.000$	45/59 $p<0.001$*	24/56 $p=0.350$	40/57 $p=0.003$*	48/59 $p<0.001$*	35/57 $p=0.111$	33/50 $p=0.033$*	11/58 $p<0.001$*	53/56 $p<0.001$*	42/54 $p<0.001$*	7 Hz
			41/60 $p=0.006$*	48/60 $p<0.001$*	9/60 $p<0.001$*	59/60 $p<0.001$*	57/60 $p<0.001$*	38/60 $p=0.052$	43/60 $p=0.001$*	14/59 $p<0.001$*	52/60 $p<0.001$*	43/60 $p=0.001$*	18 Hz
32	22	F	38/59 $p=0.036$*	41/59 $p=0.004$*	15/59 $p<0.001$*	51/57 $p<0.001$*	51/58 $p<0.001$*	34/60 $p=0.366$	42/60 $p=0.003$*	36/57 $p=0.063$	31/59 $p=0.795$	26/60 $p=0.366$	Sham
			37/60 $p=0.092$	41/60 $p=0.006$*	12/59 $p<0.001$*	57/60 $p<0.001$*	48/60 $p<0.001$*	33/59 $p=0.435$	31/60 $p=0.897$	37/60 $p=0.092$	30/60 $p=1.000$	29/30 $p<0.001$*	7 Hz
			43/60 $p=0.001$*	45/59 $p<0.001$*	9/58 $p<0.001$*	57/60 $p<0.001$*	58/60 $p<0.001$*	37/60 $p=0.092$	38/58 $p=0.025$*	50/59 $p<0.001$*	23/57 $p=0.185$	18/58 $p=0.005$*	18 Hz
33	25	F	47/60 $p<0.001$*	51/60 $p<0.001$*	11/59 $p<0.001$*	59/60 $p<0.001$*	57/60 $p<0.001$*	35/60 $p=0.245$	43/60 $p=0.001$*	24/60 $p=0.155$	44/60 $p<0.001$*	45/58 $p<0.001$*	Sham
			42/60 $p=0.003$*	54/59 $p<0.001$*	12/60 $p<0.001$*	60/60 $p<0.001$*	56/60 $p<0.001$*	29/60 $p=0.897$	36/60 $p=0.155$	25/60 $p=0.245$	48/60 $p<0.001$*	42/60 $p=0.003$*	7 Hz

			43/58 $p<0.001$*	48/58 $p<0.001$*	23/58 $p=0.148$	55/59 $p<0.001$*	56/59 $p<0.001$*	33/59 $p=0.435$	33/59 $p=0.435$	22/59 $p=0.067$	45/60 $p<0.001$*	36/59 $p=0.117$	18 Hz
34	26	F	45/59 $p<0.001$*	40/59 $p=0.009$*	12/59 $p<0.001$*	56/59 $p<0.001$*	56/59 $p<0.001$*	48/60 $p<0.001$*	46/60 $p<0.001$*	17/59 $p=0.002$*	56/59 $p<0.001$*	53/60 $p<0.001$*	Sham
			41/59 $p=0.004$*	41/58 $p=0.003$*	13/56 $p<0.001$*	51/57 $p<0.001$*	47/56 $p<0.001$*	41/60 $p=0.006$*	35/60 $p=0.245$	18/60 $p=0.003$*	47/60 $p<0.001$*	51/60 $p<0.001$*	7 Hz
			47/60 $p<0.001$*	45/60 $p<0.001$*	15/60 $p<0.001$*	56/60 $p<0.001$*	51/60 $p<0.001$*	43/60 $p=0.001$*	43/60 $p=0.001$*	25/60 $p=0.245$	58/60 $p<0.001$*	47/60 $p<0.001$*	18 Hz

Appendix E

Table S2: Post-hoc comparisons of all the GLMMs.

	Comparison	OR	Lower CI	Upper CI	SE	*z*	*p* adjusted
Model on numerical discrimination	congruent / incongruent	0.600	0.539	0.667	0.023	-13.524	< 0.001 *
	congruent / large	0.655	0.590	0.728	0.025	-11.245	< 0.001 *
	congruent / small	0.759	0.684	0.842	0.028	-7.411	< 0.001 *
	congruent / illusion	0.887	0.799	0.984	0.033	-3.233	0.001 *
	incongruent / large	1.093	0.981	1.217	0.042	2.312	0.021 *
	incongruent / small	1.265	1.137	1.408	0.048	6.181	< 0.001 *
	incongruent / illusion	1.479	1.330	1.645	0.056	10.328	< 0.001 *
	large / small	1.158	1.041	1.287	0.044	3.872	< 0.001 *
	large / illusion	1.353	1.218	1.504	0.051	8.035	< 0.001 *
	small / illusion	1.169	1.053	1.298	0.044	4.180	< 0.001 *
Model on continuous quantity discrimination	congruent / incongruent	0.068	0.060	0.078	0.003	-57.449	< 0.001 *
	congruent / large	0.182	0.162	0.204	0.007	-41.927	< 0.001 *
	congruent / small	0.190	0.169	0.213	0.008	-41.084	< 0.001 *
	congruent / illusion	0.092	0.082	0.105	0.004	-53.858	< 0.001 *
	incongruent / large	2.668	2.344	3.037	0.123	21.283	< 0.001 *
	incongruent / small	2.787	2.450	3.171	0.128	22.322	< 0.001 *
	incongruent / illusion	1.356	1.181	1.556	0.067	6.197	< 0.001 *
	large / small	1.045	0.934	1.168	0.042	1.096	0.273
	large / illusion	0.508	0.450	0.574	0.022	-15.531	< 0.001 *
	small / illusion	0.486	0.431	0.549	0.021	-16.611	< 0.001 *
	18 hz / 7 hz	1.111	1.024	1.206	0.038	3.080	< 0.01 *
	18 hz / control	1.061	0.978	1.152	0.036	1.732	0.125

	7 hz / control	0.955	0.881	1.035	0.032	-1.363	0.173
Overall model: comparison between numerical and continuous quantity discrimination	congruent / incongruent	0.206	0.189	0.224	0.006	-52.897	< 0.001 *
	congruent / large	0.349	0.323	0.377	0.010	-38.104	< 0.001 *
	congruent / small	0.384	0.356	0.415	0.011	-34.937	< 0.001 *
	congruent / illusion	0.291	0.268	0.315	0.008	-43.033	< 0.001 *
	incongruent / large	1.697	1.56	1.846	0.051	17.671	< 0.001 *
	incongruent / small	1.867	1.718	2.030	0.056	20.999	< 0.001 *
	incongruent / illusion	1.414	1.296	1.542	0.044	11.200	< 0.001 *
	large / small	1.100	1.019	1.188	0.030	3.483	< 0.001 *
	large / illusion	0.833	0.769	0.903	0.024	-6.350	< 0.001 *
	small / illusion	0.757	0.699	0.820	0.022	-9.745	< 0.001 *
	18 Hz / 7 Hz	1.063	1.008	1.122	0.024	2.729	0.019 *
	18 Hz / control	1.009	0.956	1.065	0.023	0.388	0.698
	7 Hz / control	0.949	0.900	1.001	0.021	-2.358	0.028 *
	Continuous quantity / numerical discrimination	1.469	1.418	1.523	0.027	21.065	< 0.001 *
	Continuous quantity: congruent / incongruent	0.071	0.062	0.081	0.003	-57.23	< 0.001 *
	Continuous quantity: congruent / large	0.187	0.165	0.211	0.008	-41.701	< 0.001 *
	Continuous quantity: congruent / small	0.195	0.173	0.220	0.008	-40.802	< 0.001 *
	Continuous quantity: congruent / illusion	0.096	0.084	0.109	0.004	-53.69	< 0.001 *
	Continuous quantity: incongruent / large	2.636	2.295	3.028	0.121	21.162	< 0.001 *
	Continuous quantity: incongruent / small	2.752	2.398	3.159	0.126	22.194	< 0.001 *

	Continuous quantity: incongruent / illusion	1.351	1.165	1.566	0.066	6.159	< 0.001 *
	Continuous quantity: large / small	1.044	0.926	1.177	0.041	1.088	0.277
	Continuous quantity: large / illusion	0.512	0.450	0.584	0.022	-15.462	< 0.001 *
	Continuous quantity: small / illusion	0.491	0.431	0.559	0.021	-16.513	< 0.001 *
	Numerical: congruent / incongruent	0.599	0.534	0.671	0.023	-13.537	< 0.001 *
	Numerical: congruent / large	0.654	0.584	0.733	0.025	-11.27	< 0.001 *
	Numerical: congruent / small	0.758	0.677	0.849	0.028	-7.408	< 0.001 *
	Numerical: congruent / illusion	0.886	0.792	0.991	0.033	-3.255	0.001 *
	Numerical: incongruent / large	1.093	0.973	1.227	0.042	2.303	0.022 *
	Numerical: incongruent / small	1.267	1.129	1.421	0.048	6.208	< 0.001 *
	Numerical: incongruent / illusion	1.480	1.320	1.660	0.056	10.332	< 0.001 *
	Numerical: large / small	1.159	1.034	1.300	0.044	3.902	< 0.001 *
	Numerical: large / illusion	1.355	1.209	1.519	0.051	8.051	< 0.001 *
	Numerical: small / illusion	1.169	1.044	1.308	0.044	4.166	< 0.001 *