Aalto University
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Investigating via Transcranial Magnetic Stimulation (TMS) the interaction between Visual Short Term Memory (VSTM) and mental imagery in the Early Visual Cortex (EVC).

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Aalto University School of Science Master's Programme in Brain and Mind		ABSTRACT OF THE MASTER'S THESIS
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Abstract:

Visual mental imagery and visual short term memory are often assumed to play similiar roles. There are many evidence showing that they both involve visual cortical neurons which encode incoming sensory information. On the cognitive level it has been explained in terms of the visual cache, which is nvolved in the maintenance of visual short term memory and imagery content. Even though menatl imagery and visual short term memroy may share cogntive resources, they are nevertheless two distinct psychological processes that can be dissociated behaviorally. In this study, we wanted to see if those two processes diverges in early visual cortex. To be able to do it, we used transcranial magnetic stimualtion as a probe of visual cortical activation state. Experiment consists of three diffrent blocks: VSTM alone, mental imagery alone and concurrent VSTM and imagery. The concurrent condition was carried out to understand how imagery and VSTM might interact when they are engaged simultaneously.

Keywords: Transcranial magnetic stimulation, Visual Short term memory, Mental imagery, Early Visual Cortex

Preface

This master's thesis was written at the Aalto TMS laboratory situated in the Magnet House at the Aalto School of Science during the autumn and spring of 2013/2014.

First and foremost I would like to thank my advisor, Elyana Saad, for her great instruction, being patient and always helpful during long measurements days. Your dedication to the subject gave me a lot of inspiration and motivated me in hard times. Your support, your critical minds and your advice have meant so much to me, and this thesis would not have been possible without you.

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I would also like to thank Juha Silvanto for giving me the opportunity to work on experimental setup.

The opportunity to undertake this research project could not have occurred without the wonderful support of my family to whom I am deeply grateful.

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Symbols and abbreviations

Symbols

B	Magnetic field
C	Path of the coil windings
dl	Differential length of the coil
E	Electric field
r	Position
t	Time
z	Distance from the coil along the central axis
	Permeability of vacuum

Abbreviations

EVC	Early visual cortex
LGN	Lateral geniculate nucleus
MT	Medial temporal
rTMS	Repetitive transcranial magnetic stimulation
TMS	Transcranial magnetic stimulation
VSTM	Visual short term memory
V1	The primary visual cortex
V2	The secondary visual cortex
V4	The visual area four

1. Introduction

Studies on visual cognition have focused extensively on two main cognitive abilities: visual short-term memory (VSTM), which is a subdivision of the visuo-spatial working memory (Baddeley and Hitch, 1974; Baddeley, 2001), and visual mental imagery.

Visual mental imagery and visual short-term memory are often considered as one ability due to a rising number of evidence showing the overlap of their neural bases at the level of the early visual cortex (Sparing et al., 2002; Slotnick et al., 2005; see e.g. Postle, 2006 for review,; Serences et al, 2009; Harrison & Tong, 2009; Van de Ven et al, 2012; Albers et al., 2013). Also, at cognitive level, Logie (1995) suggests that both are maintained at the level of the visual cache, a subcomponent of the visuo-spatial working memory.

At cognitive process, VSTM and mental imagery have been shown to differentially affect the encoding of internal input (Saad & Silvanto 2013), and dynamic visual noise to impair visual imagery generation but not short term memory (Quinn & McConnell, 1996; Andrade et al., 2002; Zimmer and Speiser, 2002). Therefore though mental imagery and visual short term memory share neural resources however they remain two distinct psychological processes that can be dissociated behaviorally.

Here we wanted to investigate whether transcranial magnetic stimulation (TMS) will dissociate metal imagery and VSTM during the maintenance phase when applied at the EVC. To attain this aim we used repetetive transcranial magnetic stimualtion (rTMS).

Transcranial magnetic stimulation has been used before to investigate both VSTM and mental imagery when applied at EVC. In details, Cattaneo et al.

(2009) compared the functional contribution of EVC in short-term memory retention and visual mental imagery at different delays of the retention. They showed that TMS pulses applied at later phase of the retention affect both processes.

The experiment detailed in this thesis is based on two main Experiments; Experiment 1 assesses VSTM and mental imagery when each was processed alone. Experiment 2 assesses VSTM and mental imagery when both were conducted simultaneously. This study was conducted at Aalto TMS laboratory located at Aalto University in Espoo, Finland.

2. Background

2.1 CEREBRAL CORTEX

The cerebral cortex is constituted of two hemispheres. The surface area of the human cerebral cortex is about 2,200 to 2,400 square centimeters due to its folded nature as about two thirds of its volume is confined within the depths of the sulci (Michael et al., 2009). The cyto-archtecture of the cerebral cortex consists of six layered structure called neocortex and of two principal types of neurons: the stellate cells receive sensory input and process information on a local level. These cells have different shapes, and sizes. As to the Pyramidal cells, which are more numerous, their axons have extensive local collaterals. They widespread as they leave the cortex to form connections with other parts of the central nervous system. The number of synapses on a pyramidal neuron is estimated to be between 1,000 to 10,000.

The cerebral hemispheres have been defined in terms of lobes (Figure 1). These lobes have a variety of functional roles in the neural processing. The four lobes are: the frontal, the parietal, the temporal, and the occipital lobe. The frontal lobe plays major role in planning, memorizing, mood regulation emotions, and voluntary motor function. The parietal lobe is located posterior to the central sulcus and anterior to the occipital lobe. It receives and integrates general sensory information such as taste and some visually processed information. The temporal lobe is located lateral and ventral to the Sylvian fissure. It plays a major role in the primary and the secondary processing of auditory stimuli, smell, learning, and memory. The occipital lobe is located in the posterior part of the cortex and act as the primary visual center of brain. This thesis will

mainly develop information visually processed as it investigates the neuronal correlates of their maintenance phase at EVC.

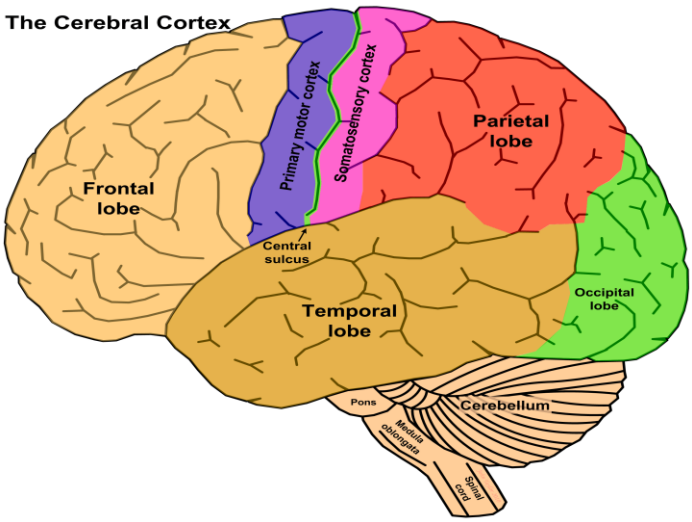


Fig.1 Division of cerebral cortex

2.2 VISUAL SYSTEM

The decoding of Visual information based on external input undergoes different steps. Starting from retinal input, traveling through the central visual system, till reaching the EVC.

2.2.1 THE EYE

The journey of a visual input starts at the level of the eye. The eye is located in the front part of the orbit.

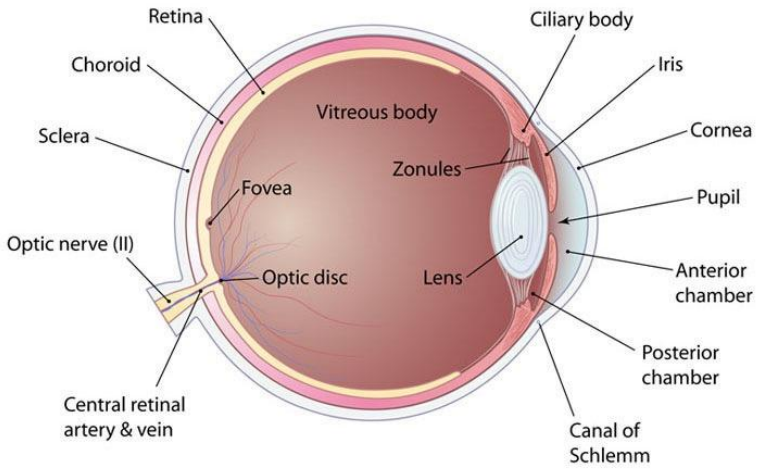


Fig.2 The conformation of eye. (Adapted from www.illuminationstudios.com)

It is constituted by three layers: the sclera, the choroid, and the retina. The sclera, also referred to as the cornea, is thick, rigid and opaque. The cornea protects the inner structures of the eye. The front of the cornea forms the sclera which is thinner and transparent. The outer layer of the sclera is composed of the epithelium and the conjunctiva. When the light passes through the cornea it undergoes refraction that is why it acts as a lens focusing the light. The most inner layer of the eye is the retina. It consists of 10 layers; it is transparent and sensitive to light. The retina is composed of photoreceptor, interneurons, bipolar cells, horizontal cells, and ganglion cells. The photoreceptors are divided into two types, rods and cons cells. The rods are located throughout the retina, but greater number is located on the fringes. They are not sensitive to colors, but allow the perception of shapes and movement in low light vision or scotopic vision. The highest density of cons cells occurs in the macula in the central part of the retina, thus corresponding to the sharpest vision. Cones are found at the fovea level, which is the area of the retina that perceives the central visually presented information. The light

energy received by the photoreceptors is converted into electrical signal that is readable by the brain. The size of the receptive field of retinal ganglion cell depends on the area of the retina from which they emerge. The farther away from the fovea the larger the receptive fields. The peripheral regions of the retina receive input from a higher number of photoreceptors causing higher sensitivity to low levels of light. On the other hand, the fovea receives less input from the photoreceptors, making it more sensitive to high spatial frequencies. Ganglion cells have a center surround organization. There are three main types of ganglion cell: magnocellular (M), parvocellular (P) and koniocellular (non-M, non-P or K). Information goes from the rod and cone through bipolar cells to ganglion cells, which axons form the optic nerve.

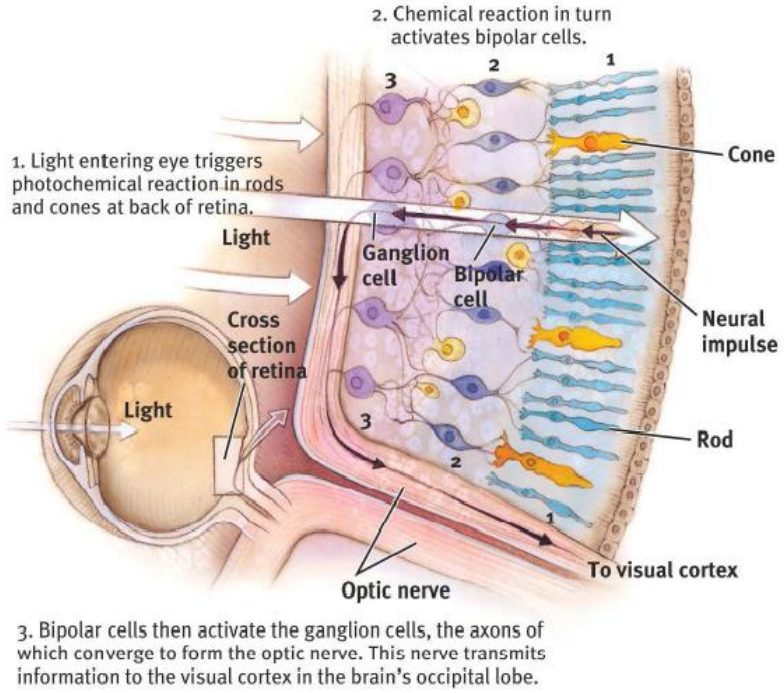


Fig.3 The pathway of visual system. Light fall on the retina and create a photochemical reaction in the roads and cones at the back of the retina. The reaction then continues to the bipolar cells, the ganglion cells and eventually to the optic nerve.

2.2.2 THE CENTRAL VISUAL SYSTEM

Optic nerves, from both eyes, meet at the optic chiasm and become the two optical pathways. Which differ with respect to where they terminate at the subcortex level. These include the lateral geniculate nucleus in the thalamus, the superior colliculus in the brainstem, and the suprachiasmatic nucleus in the hypothalamus**.** The superior colliculus retains the retinotopic map and is responsible for tracking eye-movements and for spatial orientation.

The optic pathways connect the optic chiasm to the lateral geniculate nucleus, creating geniculostriate pathway which is the final projection to the visual cortex.

At the level of LGN, ganglion cells, innervated by cones, transmit the signal to the parvocellular to the dorsal LGN layers (layers 3-6). This pathway is responsible for the transmission of fine grain; color visual information from the central regions is transmitted to primary visual cortex layer 4C-β (Livingstone & Hubel, 1988, Casagrande & Kaas, 1994 for review). Ganglion cells innervated by rods transmit the signal to the Magnocelluar layers (layer 1 and 2) at the ventral LGN. These M neurons are characterized by sensitivity to high contrast, and motion. The M neurons send the signal to the primary visual cortex layer 4C- α (Livingstone & Hubel, 1988, Casagrande & Kaas, 1994 for review). A third less documented LGN cell class are the Koniocellular cells.

2.2.3 THE OCCIPITAL LOBE AND EARLY VISUAL AREAS

The occipital lobe, known as the visual cortex, form the posterior pole of the cerebral hemispheres, and is lying in the back of the skull. The occipital lobe is separated from the parietal lobe by the parieto-occipital sulcus. The visual cortex is divided into three major landmarks: calcarine sulcus, lingual gyrus and fusiform gyrus. The whole occipital lobes are divided into nine different visual areas, named V1, V2, V3, VP, V3a V4d, V4v, DP and MT/V5. V1 also known as primary visual cortex, which receives the largest input from the lateral geniculate nucleus and project that information to other levels. V2 is the secondary visual cortex, projects information to higher levels and acts as an output to the parietal lobe (visual guidance of movements), the inferior temporal lobe (object perception), and the temporal sulcus (visuospatial functions). Information about color and shapes are transmitted from V1 to V4. Information from area V1 and V2, about motion, goes to V5. Finally, information about the shape of object motion travels from V1, V2 to V3.

As the main aim in the thesis is the early visual cortex, I will therefore detail the primary visual cortex.

V1 is located at the medial surface of the cerebral hemispheres and is extending slightly onto the posterior hemispheric pole. The average number of neurons in the adult human primary visual cortex, in each hemisphere, has been estimated to140 million approximately (Leuba & Kraftsik, Anatomy and Embryology, 1994). The visual cortex is constituted by six layers (1, 2 layers are magnocellular and 3,4,5,6 are parvocelluar see figure 4). At the level of these

layers resides the staring process of the cortical coding of visual features such as color, luminance, spatial frequency, orientation, and motion. There are three types of cells or neurons in the Primary Visual Cortex (V1): Simple Cells which Respond to bars of light. Complex Cells which Respond to line orientation in or out of its excitatory/ inhibitory zone and Hyper Complex Cells which respond to moving corners or angles. In the center of every layer we can find blobs interlayer with interblobs. The blob contains color sensitive double opponent cells with circular surround receptive field. Blob cells contain single eye information and interblobs contain mixed information from both eyes (Livingstone & Hubel, 1988).

From V1 information is transmitted to two primary pathways called the dorsal stream and the ventral stream: The dorsal stream begins with V1, goes through visual area V2, and then reaches the dorsomedial area, MT and to the posterior parietal cortex. As to the ventral stream it begins at V1 levels goes through V2, V4, and reaches the inferior temporal cortex.

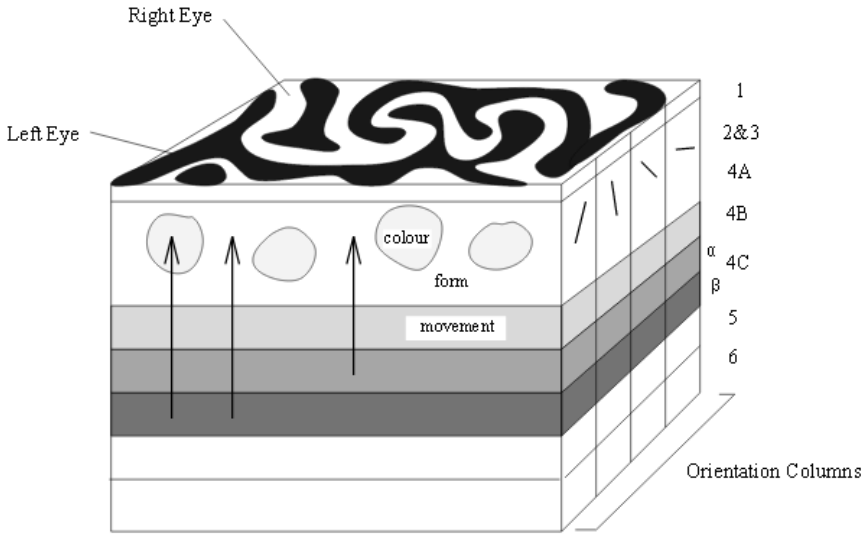


Fig.4 The structure of primary visual cortex. Adapted from Livingstone (Livingstone & Hubel, 1988)

V1 has a very well-defined map of the spatial information in vision. The correspondence between a given location in V1 and the subjective visual field is very precise. A large portion of V1 is mapped at the fovea level. (Tai Sing Lee, 2003). Visually retained information will be processed by the working memory.

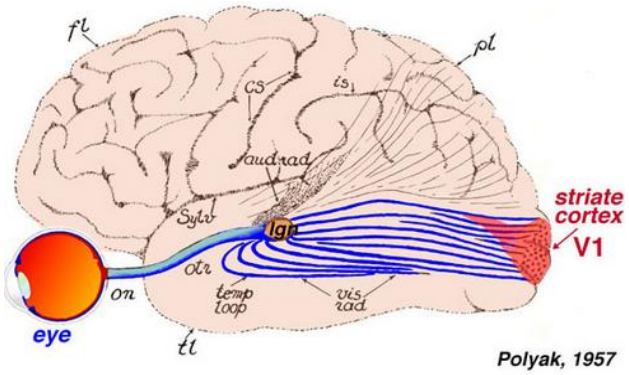


Fig.5 Visual input travel from eye to LGN and then to early visual cortex located in the occipital lobe. Adapted from Polyak (1957)

2.3 WORKING MEMORY

We are in need in our day to day life to keep some information in our memory for short term: i.e., remembering phone numbers names, doing some basic math. These are simple tasks that we are faced with on a daily basis. However, some difficulties might arise when faced with more complicated tasks. to illustrate: remembering directions, map and specific driving instructions requires beside holding information in mind, performing some cognitive operation such as following cues and overcoming instantaneous obstacles.

These short term mental storage and the cognitive manipulation that is bestowed upon retained information well define the working memory.

The very first distinction between short-term (primary memory) and long-term (secondary memory) memory was introduced by the American psychologist William James in 1890. He suggested, that in primary memory information is stored and available to conscious inspections at any time ("an object of primary memory is thus not brought back; as it is never lost" W. James, 1890). On the other hand, secondary memory is a storage system where information cannot be retrieved without ongoing cognitive process. In 1956, the classical finding by Miller, stated in "The Magical Number Seven, Plus or Minus Two" paper, showed that people have a limited ability in receiving processing and recalling information (G. Miller, 1956). In his experiment, he shows that subjects are able to store in a short-term memory about seven items. Therefore he suggested that single items can be grouped into chunks. With this new concept, Miller highlighted that the short-term storage capacity is expandable. Brown and Peterson requested from their (Brown, 1958; Peterson & Brown, 1959) participants to recall trigrams (meaningless three-consonant syllables) after different intervals. To prevent rehearsal, they were asked to simultaneously count backwards until seeing a red light. The results revealed that the longer the delay, the less number of trigrams was recalled. This experiment showed that short- term memory has limited time span and is different from long- term memory in terms of duration. An additional differentiation between short and long term memory was proposed by Atkinson and Shiffrin (Atkinson & Shiffrin, 1968). In their model (referred to as the multistore model) short term-memory serves as a pathway by which information can gain access to long-term memory. On the basis of the Atkinson & Shiffrin model, Baddeley and Hitch (1974) developed a more detailed system that better explained the working

memory system. In their first experiment, they asked people to make true-false decisions about spatially arrayed letters. On trial by trial basis participants were asked to repeat all digits that were shown on the screen (between 6 and 8 digits). The results showed that subjects did not do more errors when simultaneously they were holding digit strings in short-term and counting backwards. This suggested that there exist multiple systems for working memory which are coordinated by the central executive mechanism. The original formulation of Baddeley's model consists of three different components:

- Central executive – key component, limited capacity, deals with cognitively demanding tasks
- The visuospatial sketchpad – limited capacity, storage of visual and spatial information
- The phonological loop – limited capacity, preserve order in which words are presented

In 2001 Baddeley added a fourth component: the episodic buffer:

- Episodic buffer – limited capacity, deals with and binds information from different modalities.

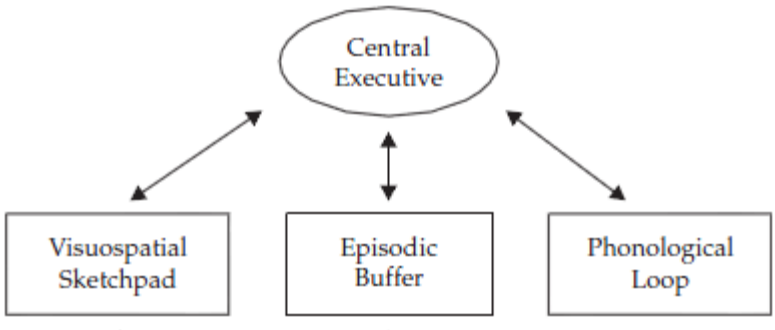


Fig.6 Baddeley model of working memory. Adapted Baddeley, 2000.

The central executive is the most important component of working memory. It has no storage capacity.

Baddeley (1996) identified after a set of experiments the functions that describe the central executive: switching of retrieval plans, timesharing in dual-task studies, selective attention, and temporary activation of long-term memory.

According to Baddeley (1986, 1990) the phonological loop is described as a passive and time limited storage of auditory based material. It is believed, that it is located in the left hemisphere of the brain (Logie et al., 2003). The Phonological loop is divided into two components: the phonological store and the articulatory rehearsal mechanism. Basically, the length of the word has a meaning. Thus the ability to reproduce a sequence of words is higher with short words than longer ones (Baddeley et al., 1975). This suggests that the capacity of the phonological loop is determined by the temporal duration, and that the memory span is determined by the rate of rehearsal.

The visuospatial sketchpad is the second slave storage system. It is believed to be located in the right hemisphere of the brain. It holds visual and spatial information for a short period of time. At this point, it is worth to mention the work done by Logie (1995). Logie proposed two components of visuo-spatial working memory: the visual cache, and the inner scribe. The visual cache is a passive store which is responsible for the storage of visual information like color and form. The second component, inner scribe, is described as more active system. It is responsible for dealing with spatial and movement information and rehearses information and transfers information in the visual cache to the central executive ((Beschin et al., 1997; Smith & Jonides, 1997).

The episodic buffer is controlled by the central executive through the medium of conscious awareness and it acts as a system which integrates information from a range of sources into a single coherent memory experience (Baddeley & Wilson, 2002). The capacity of the episodic buffer is limited; however it also acts as an extra storage mechanism to back up other storage areas.

2.4 VISUAL SHORT TERM MEMORY

Quite often perceived information is store in a short-term format, this process is referee to as visual short-term memory (VSTM; Phillips, 1974; Phillips & Christie, 1977). VSTM representations are resistant to minor distractor; in the sense that they survive eye movements, and eye blinks. VSTM is a short-term, active store for visual information that has not yet been encoded into long-term memory (Baddeley, 1986). These representations are formed very quickly and are capacity limited (Baddeley,1986; Baddeley & Logie, 1999) areas which are believed to be essential to the VSTM consists of occipitotemporal, frontal, prefrontal and parietal cortex, the anterior cingulate and the basal ganglia. HaxEby and collaborators performed an experiment using functional magnetic resonance, to investigate the human neural system of visual working memory (Haxeby et al., 2000). In their study, Subjects performed spatial and face memory tasks. Different areas were activated during stimulus presentation and memory delays. Whereas the Inferior frontal gyrus, posterior middle frontal gyrus, anterior middle frontal gyrus showed higher activation during memory delays and reaction to face stimuli, the anterior region showed stronger

memory maintenance related activity. Prefrontal cortex was activated throughout all memory tasks.

Sneve et al, (2011) found that BOLD (blood oxygen level dependent) activity at V1 level, during delayed match-to-sample task and within a memory masking set up of varying spatial frequencies was weaker when performances were impaired by the presence of the mask stimuli. These weaker responses were observed in regions that were engaged in the retention of visual information.

Additional studies on visual short term memory revealed that the amount of stored information that follows a briefly viewed image, is very small. Sperling (1960) found that observers could remember only 4 letters on average, regardless of how long they viewed different sized matrices of letters. In another experiment, Luck & Vogel (1997) found that only four integrated objects, such as colored boxes, are retained during change detection tasks.

However, Alvarez and Cavanagh (2004) suggested that the capacity of VSTM is not limited by the number of objects, but by information load. In their study they used a change detection paradigm by presenting six different stimulus types: colors, letters, Chinese characters, random polygons, shaded cubes, and Snodgrass drawings (Snodgrass & Vanderwart, 1980). The capacity of VSTM varied for each stimulus type. They concluded that the greater the informational load, the less information can be retained in visual short term memory. Luria et al., measured the capacity of visual short term memory for simple and complex stimuli. Thus, they presented either colored squares or random polygons to subjects. Participants were instructed to memorize the stimulus that was cued by an arrow, and judge whether the memory and the test array were identical. The results revealed that more resources and efforts were employed when maintaining complex objects.

2.5 MENTAL IMAGERY

One of the pioneering works that studied the role of imagery in thinking was conducted by Sir Francis Galton in 1883. In Galton's *"breakfast-table questionnaire"* he asked subjects to think about their breakfast table and imagine it in front of their mind's eye. What was most commonly report is a "mental vision."(Bruno Laeng & Unni Sulutvedt, 2013).

A pioneering classical work by Perky (1910) will shed more light on mental imagery processes. Perky asked her subjects to look at the fixation point on a screen and visualize various objects, such as a tomato (red), a book (blue), a leaf (green), a banana (deep yellow), an orange (orange), or a lemon (light yellow).Perky was projecting a very dim image of those objects onto the screen. None of the Perky's subjects realized that on the screen was an actual picture. Some subjects expressed surprise at finding themselves imagining a banana "upright" rather than the horizontally oriented when describing these pictures.

Years later during Kosslyn's investigation (1973), participants had to study picture of items. Presented pictures had three easily distinguished parts: two ends and the middle. Subjects afterwards were asked to generate mental images of items and then to look for a particular part of pictured item. Kosslyn's investigating led to the conclusion that More complex forms require more time to image (Kosslyn, 1988) and the response time is affected by the spatial nature if images. Based on many of these experiments Kosslyn suggested different stages of mental imagery process.

Thus, after mental image generation, it is stored into topographically organized area. This organized area is called visual buffer and it is located in the early visual cortex (Kosslyn, 1980, 1994; Kosslyn & Thompson, 2003; Kosslyn et al., 2006). The second step involves transferring the content from visual buffer into the visual cache. The main task for the visual cache is to allow the process of encoding and maintaining of short-term visual representations and mentally generated images (Logie 1995). In the third step is for the interpretation of memorized objects' features and spatial properties (Kosslyn et al., 2001). The last step of the process is described as transformation and manipulation, such as mental rotation (Shepard & Cooper, 1982) or reconstruction of images (Reisberg & Logie, 1993).

In 1985, Farah conducted two experiments which explore the relation between the representational structures activated by visual imagery and visual perception (Farah, 1985). During the first experiment, subjects were asked to imagine on the screen either the letter H or T. Once they formed clear image, they pressed a button that caused two squares flash one after the other. One of them had a target letter (either an H or T). Subject's task was to indicate if the letter was on the first or on the second square. In the second experiment, subjects had the same task with three main differences: the imagery cues were different, trials were not subject-initiated and there were a larger number of conditions. The result showed that participants were more accurate in perceiving a real stimulus after that they have imagined the stimulus. Farah concluded, that imagery and perception share common structures.

In 1989 Finke's proposed five principles of visual Imagery:

1) Mental imagery is often implicitly encoded. That means that information is encoded unconsciously.

2) Mental imagery is equivalent to perception. The same area is activated when we create a mental image and when we perceive visual stimuli.

3) Mental imagery is spatially equivalent. The spatial organization of the elements of mental image is arranged in similar fashion to the real space.

4) Mental image is transformational equivalent. Manipulation of mental images is similar to manipulation of real objects (i.e., the rotation of objects to fit to the main picture (Shepard and Metzler, 1971)).

5) Mental image is structural equivalence. The structure of mental images is similar to structure of real object. As it was mention above, larger objects take more time to be mentally created and look over them.

Ganis et al. (2004) used functional magnetic resonance (fMRI) to see if there is a difference in activation in areas, between perception and imagery. Participants were asked to either close their eyes and visualize an object or observe faint drawings of objects. They additionally, were asked to judge some aspect of the drawing. The Results showed that many areas of brain were activated during both conditions. Figure 7, shows a common overall pattern of activation.

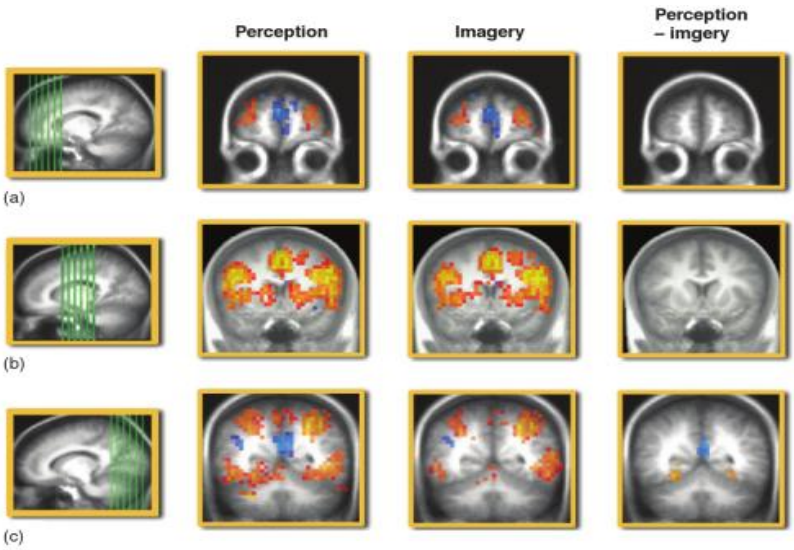


Fig.7 Brain scan from work done by Ganis et al. 2004. A) Response from frontal lobe. The lack of colour on last picture shows that activation was the same in imagery and perception condition. B) Response from temporal cortex. Activation in brain for perception and imagery was same as previous. C) Response from the back. It is visible that response in the perception condition was greater than in imagery condition.

3. Transcranial Magnetic Stimualtion

3.1 SHORT HISTORY OF TRANSCRANIAL MAGNETIC STIMULATION

The technique of transcranial magnetic stimulation is based on the phenomenon of electromagnetic induction, first described by Michael Faraday in 1831 (Jalinous, R. Guide to Magnetic Stimulation. The Magstim Company Limited, spring Gardens, UK, 1995). If a very brief, but strong electric current is passed through a coil of wire it generates a changing magnetic field, which in turn induces a current in an adjacent wire circuit or volume conductor (Faraday's law). D'Arsonval in 1896 was the first to place subjects head inside a powerful magnetic coil (110V, 30A, 42Hz) to produce phosphenes, vertigo and syncope. (D'Arsonval 1896) Few years later in 1902, Beer showed in his work that phosphenes could be produced by applying a magnetic field to region responsible for vision. In 1965, Bicford and Fremming for the first time used magnetic pulses of 2-3T to twitch skeletal muscle. In 1985 Baker constructed the first modern TMS with his colleagues. The Sheffield group conducted for the first time stimulation over the motor cortex. This technique was painful; however, they recorded twitches in hand muscles for about 25 ms (Barker et al., 1985). Since 1985, magnetic stimulator technology has remained mostly unchanged. Whereas early research used circular coils, today devices are usually equipped also with a figure-eight (double or butterfly) coil proposed by Ueno. It is estimated that stimulation of figure eight coil reach up to 5mm below the coil and cover an area of 6cm approximately.

Repetitive TMS delivers trains of stimuli at 1-50 Hz. rTMS was first produced by Cadwell Laboratories in 1988. Some types of coil uses also a forced air flow to cool the surface of the coil, so it can be used for long trains of pulses.

Fig.8 Two types of TMS coil: circular coil on the left and figure eight on the right.

3.2 PHSICS OF TRANSCRANIAL MAGNETIC STIMULATION

To produce induced responses at the level of cortical neuronal population, the induced field must differ across the cell membrane. Therefore the axon has to be bent across the electrical field or the field must traverse an unbent axon (Ruohonen & Ilmoniemi, 1999). Neurons can be excited by externally applying a time-varying electromagnetic field. In TMS, excitation is achieved by driving intense pulses of current $I(t)$ through a coil located above the head. The source of activation is the electric field **E** induced in the tissue, obtained from Faraday's law:

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

Where E is the electric field in cortex and **B** is the magnetic field produced by the coil, given by the Biot- Savart law:

$$B(r,t) = \frac{\mu_0}{4\pi} I_c(t) \oint_C \frac{dl(r') \times (r - r')}{|r - r'|^3}$$

Where the permeability of vacuum, C is the path of the coil windings and dl is the differential length of the coil. The high voltage electronic switch is crucial for creating the very short pulse. The induced **E** is strongest near the coil and typically stimulates a cortical area of a few centimeters in diameter.

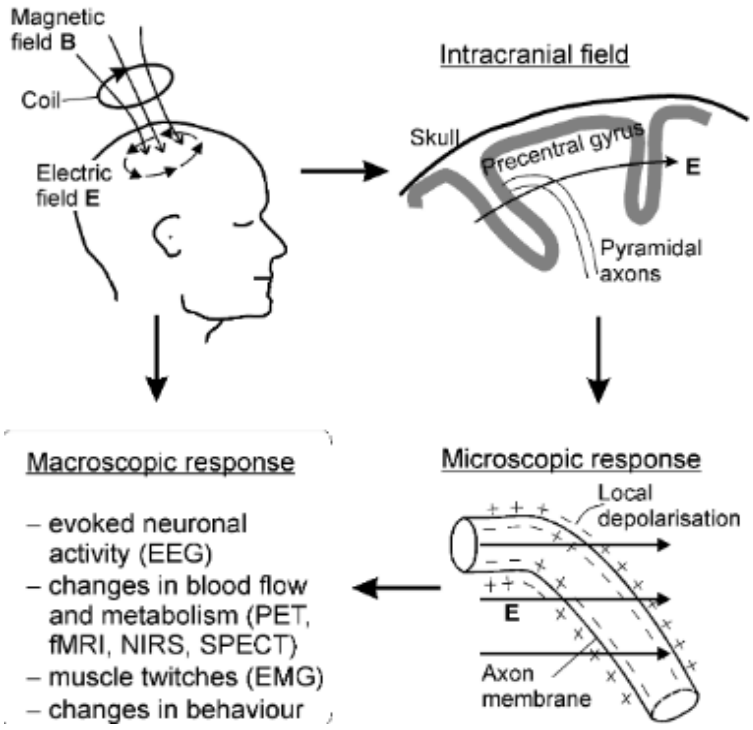


Fig.9 Representation of macroscopic and microscopic response of TMS. Adapted from Ruohonen (1998)

TMS pulses cause coherent firing of neurons in the stimulated area as well as changed firing due to synaptic input. The stored energy is transferred to the coil in approximately 0.1 ms and then returned to the instrument to reduce coil heating. Biphasic or polyphasic pulses are less accurate and produce more click noise and heat. The brief and strong discharge current of up to 5,000-8,000 amps flowing through the stimulating coil generates a magnetic pulse with a

fast rise time (0.1 ms) and slower decay (up to 1 ms), and a peak magnetic field power of 1.5-4 Tesla.

There are two main types of coils: circular coil and the figure-eight coil. Circular coils are usually about 8cm in diameter. Coil with radius R, the magnetic field along a line perpendicular to the coil and through its center is proportional to

$$B \propto \frac{R^2}{2 \cdot (R^2 + z^2)^{3/2}}$$

where z is the distance from the coil along the central axis. The site where stimulation occurs in this type of coil is at places around the loop. Figure-eight coil consist of two circular coils joint to each other in the same plane. This configuration has the effect of narrowing and decreasing in strength toward the apex.

3.3 SINGLE PULSE TMS AND REPETITIVE TMS

There are two available types of stimulation: single-pulse TMS and repetitive TMS. Both of them generate trains of stimuli at 1-60Hz. In single-pulse TMS, monophasic, biphasic or polyphasic stimulation (Fig.10), are delivered nonrythmically not more than once every few second (Wassermann 1998). This form is usually used for physiological research or diagnostic purpose. A single pulse is of value in producing a temporary lesion used to investigate attention, plastic visual detection, and evoking motor system responses.

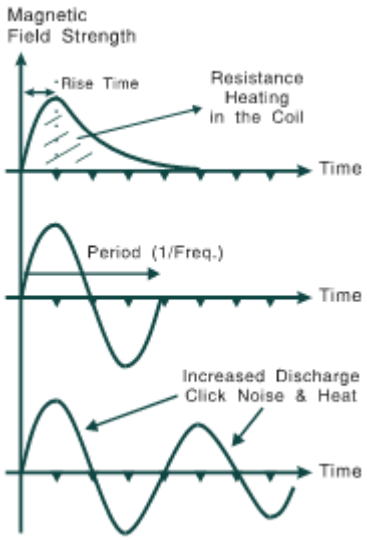


Fig.10 The waveforms of monophasic, biphasic and polypasic stimulation. Monophasic stimulation is used for rapid rate stimulator, produce less heat and noise and increase stimulus accuracy compering to other. Biphasic stimulation has short efficient pulse, produces more noise and is not as accurate as monophasic. It is best in use of studying brain connectivity. Polyphasic stimulation is very efficient but produces a lot of noise and heat.

Repetitive TMS uses short bursts at a high inner frequency interleaved by short pauses of no stimulation. There are two types of frequencies used in repetitive TMS: fixed and modulated frequencies. In fixed frequency, every pulse in a train has the same power output and intervals lasting from 20ms up to 1000ms. This type of modulation is useful in the therapeutic application. In modulated frequency, the power and intervals can varied from 1ms to 1000ms and are selected in 1/10ms steps. Modulated frequency is used in more complicated cortical investigation. Repetitive TMS produces longer-lasting effects which persist after the initial period of stimulation. rTMS can increase or decrease the excitability of the corticospinal tract depending on the intensity of stimulation, coil orientation and frequency. Lower frequencies of rTMS in the 1Hz range can suppress excitability of the motor cortex while 20Hz stimulation

trains seem to lead to a temporary increase in cortical excitability (Pascual-Leone A, 1998).

3.4 SPATIAL RESOLUTION OF TMS

An exact spatial resolution of the TMS cannot be measured in mm or cm because the effect depends on the initial activity of neurons in the stimulated region of interest (Silvanto et al., 2007) stimulation intensity (McKeefry et al., 2008) and stimulation frequency (Huang et al., 2005). Mapping the visual and motor cortex are good examples of TMS spatial resolution. Kammer (1999) showed phosphenes, which were elicited with a resolution of 1-2 degrees of visual angle are equivalent to 10-20mm of cortex. Coil Displacement as small as 1cm along the scalps surface can shift the perceived retinal location of phosphenes (Walsh & Cowey, 2000; Cowey, 2005).Furthermore, muscles in the motor cortex ,which are segregated by as little as 1 to 2 cm on the cortex, can selectively be stimulated (Brasil-Nero et al. 1992; Wassermann et al. 1992; Singh et al. 1997). The spatial resolution of TMS is highly dependent upon the shape of the stimulating coil and the temporal resolutions of TMS are variable and depended upon the stimulation parameters.

3.5 WHAT ARE PHOSPHENES?

When applied at EVC TMS induces phosphenes or illusionary flashes of light. However, the determination of phosphene threshold may not be obtainable in most of the subjects, and often requires the use of repetitive pulse stimulation (Ray et al., 1998; Boroojerdi et al., 2000). Phosphenes are considered as the electrophysiological equivalent to the induced muscle twitches caused by TMS

(T. Kammer et al., 2005). Phosphenes are usually stationary and they appear to be very brief flashes of light grey or white colour. The shape of phosphene may be different across subjects. Some describe phosphenes as straight or curved lines, while others perceive regular patches (Kammer, 1999). People who are blind also can see phosphenes. In 1755, Charles Le Roy stimulated a blind patient through the retina and cortex. The patient reported vivid phopsphenes yet blind. The brain structure which is involved in the generation of phosphenes is the primary visual cortex.

3.6 EFECT OF TRANSCRANIAL MAGNETIC STIMULATION OVER THE VISUAL CORTEX

As noted above, TMS applied over the occipital cortex can induce the perception of flashes of light called phosphene (Arsene d'Arsonval, 1910; Thompson, 1910; Ray et al., 1998; Kammer, 1999; Boroojerdi et al., 2000; T. Kammer et al., 2005,).

In Mulckhuyse et al. experiment (2011), participants were asked to perform a spatial cueing orientation discrimination task. During the experiment, single pulse TMS was applied, below phosphene threshold, before the stimulus onset. The results showed that TMS facilitated the visual processing for orientation targets and for luminance cues. Romei et al. (2008a) stimulated the visual cortex to induce phosphenes in the absence of any visual confound. Participants were blindfolded and were asked to report whether they perceived phosphenes. The Results demonstrated a reduced alpha-band activity in posterior sites contra lateral to the occipital TMS side, suggesting location-specific enhanced visual cortex excitability. Additionally, TMS affected the influence of working memory on visual search (Soto et al., 2012). Soto and

colleagues applied TMS at the early visual cortex. TMS was found to enhance search performance on valid trials relative to invalid cueing trials.

Cattaneo et al. (2009) compared the functional contribution of EVC in short-term memory retention and visual mental imagery at different moments in time. The author showed that tms applied at the beginning of the retention interval over the early visual cortex increased reaction time for memory trial, but not for imagery. However, TMS pulses applied later, affected both processes.

Also, TMS over the early visual cortex has been shown to impair performance in visual imagery tasks, thus implicating this region in imagery processes (Kosslyn et al., 1999b).

3.7 SAFETY OF TRANSCRANIAL MAGNETIC STIMULATION

Safety issues are very important during usage of TMS. That is why, every participant is required to fill in some screening forms (Fig 11). TMS studies cannot be conducted with participants who suffered from stroke or brain trauma, have surgical clips or have a pacemaker. Women who are pregnant also should not participate in TMS experiments.

The strong magnetic field pulse produced by the TMS coil can induce large voltages in nearby wires and electronic devices. Such as implants and can also result in displacement of some small metallic implants in the head (Rossi et al. 2009)

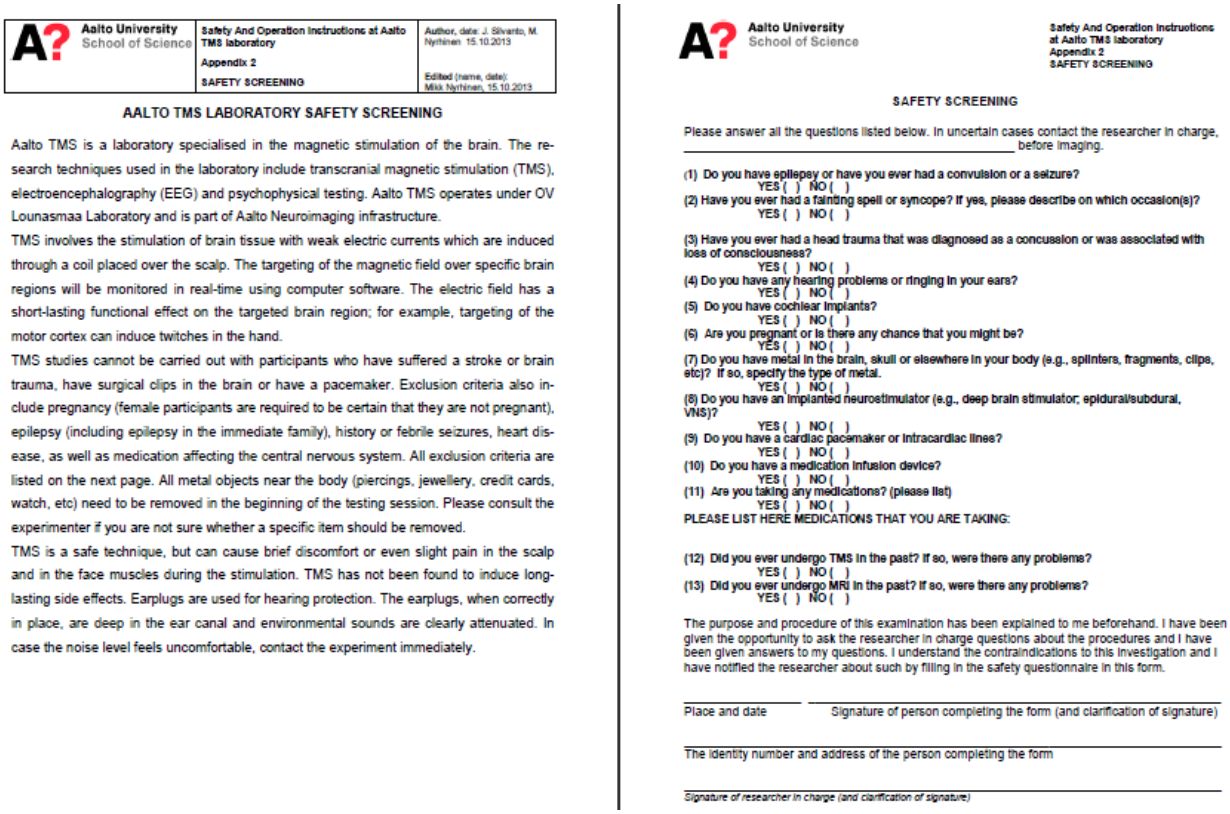
Possible side effects of TMS when the participant is not well screened are:

Seizure induction – rare in use of low frequency rTMS and more possible in high frequency rTMS

Transient headache, local pain – possible in single pulse TMS and paired pulse TMS but quite often in use of low frequency rTMS and high frequency rTMS

Transient hearing changes – possible in all types of used TMS

It is recommended that subjects use approved hearing protection (earplugs), people with cochlear implants should not receive TMS. For some people rTMS might be painful. It depends on the intensity, frequency, placement of TMS, and individual susceptibility. In the majority of patients, all types of pain disappear after some period of time.



Aalto University
School of Science

Safety And Operation Instructions at Aalto TMS laboratory
Appendix 2
SAFETY SCREENING

Author, date: J. Silvanto, M. Nythinen 15.10.2013
Edited (name, date): Mikk Nythinen, 15.10.2013

AALTO TMS LABORATORY SAFETY SCREENING

Aalto TMS is a laboratory specialised in the magnetic stimulation of the brain. The research techniques used in the laboratory include transcranial magnetic stimulation (TMS), electroencephalography (EEG) and psychophysical testing. Aalto TMS operates under OV Lounasmaa Laboratory and is part of Aalto Neuroimaging infrastructure.

TMS involves the stimulation of brain tissue with weak electric currents which are induced through a coil placed over the scalp. The targeting of the magnetic field over specific brain regions will be monitored in real-time using computer software. The electric field has a short-lasting functional effect on the targeted brain region; for example, targeting of the motor cortex can induce twitches in the hand.

TMS studies cannot be carried out with participants who have suffered a stroke or brain trauma, have surgical clips in the brain or have a pacemaker. Exclusion criteria also include pregnancy (female participants are required to be certain that they are not pregnant), epilepsy (including epilepsy in the immediate family), history or febrile seizures, heart disease, as well as medication affecting the central nervous system. All exclusion criteria are listed on the next page. All metal objects near the body (piercings, jewellery, credit cards, watch, etc) need to be removed in the beginning of the testing session. Please consult the experimenter if you are not sure whether a specific item should be removed.

TMS is a safe technique, but can cause brief discomfort or even slight pain in the scalp and in the face muscles during the stimulation. TMS has not been found to induce long-lasting side effects. Earplugs are used for hearing protection. The earplugs, when correctly in place, are deep in the ear canal and environmental sounds are clearly attenuated. In case the noise level feels uncomfortable, contact the experiment immediately.

Aalto University
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SAFETY SCREENING

Please answer all the questions listed below. In uncertain cases contact the researcher in charge, _____ before imaging.

(1) Do you have epilepsy or have you ever had a convulsion or a seizure?
YES ( ) NO ( )
(2) Have you ever had a fainting spell or syncope? If yes, please describe on which occasion(s)?
YES ( ) NO ( )

(3) Have you ever had a head trauma that was diagnosed as a concussion or was associated with loss of consciousness?
YES ( ) NO ( )
(4) Do you have any hearing problems or ringing in your ears?
YES ( ) NO ( )
(5) Do you have cochlear implants?
YES ( ) NO ( )
(6) Are you pregnant or is there any chance that you might be?
YES ( ) NO ( )
(7) Do you have metal in the brain, skull or elsewhere in your body (e.g., splinters, fragments, clips, etc)? If so, specify the type of metal.
YES ( ) NO ( )
(8) Do you have an implanted neurostimulator (e.g., deep brain stimulator; epidural/subdural, VNS)?
YES ( ) NO ( )
(9) Do you have a cardiac pacemaker or intracardiac lines?
YES ( ) NO ( )
(10) Do you have a medication infusion device?
YES ( ) NO ( )
(11) Are you taking any medications? (please list)
YES ( ) NO ( )
PLEASE LIST HERE MEDICATIONS THAT YOU ARE TAKING:

(12) Did you ever undergo TMS in the past? If so, were there any problems?
YES ( ) NO ( )
(13) Did you ever undergo MRI in the past? If so, were there any problems?
YES ( ) NO ( )

The purpose and procedure of this examination has been explained to me beforehand. I have been given the opportunity to ask the researcher in charge questions about the procedures and I have been given answers to my questions. I understand the contraindications to this investigation and I have notified the researcher about such by filling in the safety questionnaire in this form.

Place and date _____ Signature of person completing the form (and clarification of signature) _____

The identity number and address of the person completing the form _____

Signature of researcher in charge (and clarification of signature) _____

Fig.11 Safety screening questionnaire from TMS laboratory in Aalto University.

4. Neuronaviagation

Neuronavigation technique allows precision at desired stimulated areas. Thus data are recorded in real time using an ultrasound based position measurement system. The system consists of several circular trackers attached to the special bound placed on the head, on a digitizing pen and on the TMS coil. The measurement of the relative spatial position of these senders in 3d space is based on the travel time of the transmitted ultrasonic pulses. The first step consists of the creation of a local spatial coordinate system, which is a possible via the digital pen. The nasion and two pre auricular points from the subject head are used to define the real world central coordinate system. The same anatomical landmarks are also identified in the MRI scan of the subject. After this step, the movement of TMS coil is also visible on the screen.

5. Experiment

5.1 PARTICIPANTS

In the 2 experiments 23 subjects were recruited, from which nine were females (mean age 25 years old). All of them had normal vision. All were naive to the aim of the study and provided written informed consent in agreement with the Declaration of Helsinki and approved by the ethics committee of the Hospital District of Helsinki and Uusimaa.

5.2 STIMULI

Participants were seated in front of the monitor and asked to memorize and judge stimuli. The stimuli were displayed in the center of the monitor on a grey background from a viewing distance of 57 cm. All stimuli were sinusoidal luminance-modulated gratings with a diameter of 5 degrees of visual angle and were generated with custom-made software in Matlab. Gratings were vertically oriented and the spatial frequency was 1.44 cycles/degree. The memory and the imagery cues had a Michelson contrast of 0.2, 0.3, 0.4 and 0.5. Worth noticing is the fact that the difference between test cue and imagery/memory cue was +/- 0.06 or 0.09, were +/- 0.06 is associated with difficult level of dissociation and +/-0.09 with easy level of dissociation. A mask, black circle of the same diameter as stimuli appeared at main cue offset.

The display monitor was 22-inch screen with 1600x1200 pixel resolution. The software used to control both the task and stimuli was the E-prime v2.0 (Psychology Software Tools Inc., Pittsburgh, USA; http://www.pstnet.com/eprime.cfm).

5.3 D-PRIME MEASURE

D' analysis is bias-free statistics. Researchers are using d' because it allows testing weak or small effects which might otherwise be hard to detect. It allows psychologists to test the sensitivity of subjects in experiments that might be strongly influenced by belief, guess or chance.

5.4 EXPERIMENTAL SESSIONS

There were two different experiments. The first one was conducted to examine VSTM and imagery when each was conducted separately. For VSTM assessment participants were instructed to hold the cue contrast in memory, without using imagery throughout the trial. At the end of the trial, they were required to judge whether the test cue was of lower or higher contrast than the original memory cue. For the imagery assessment participants were asked to form a mental image of the original imagery cue and hold it in the mind's eye until asked to perform the discrimination task, where the individualized mental image contrast was compared to the test cue.

In the second experiment, VSTM and imagery were used simultaneously. Subjects were asked to form mental imagery and hold the cue in memory at the same time. At the end of the cue, they were informed whether memory or imagery would be assessed.

In experiment number 1, VSTM alone block and imagery alone block were run (See fig.12). Every condition consists of 2 blocks of 32 trials which were run for both TMS conditions (Early Visual Cortex, Sham). In experiment 2 (See fig. 13), concurrent VSTM and imagery were run in 4 blocks of 32 trials for both TMS conditions. The order of experiments and condition was counterbalanced.

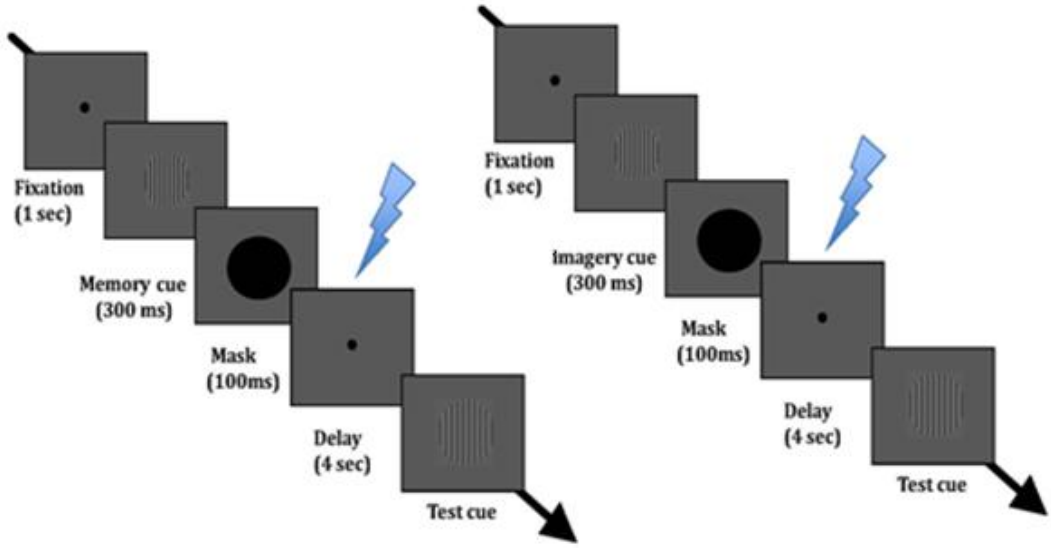

Fig.12 Timeline of the first experiment. At the start of each trial, participants were presented with a cue. The task involved maintaining the contrast of the grating by holding it in memory and/or forming a conscious mental image of it and maintaining it throughout the maintenance period. TMS pulse train was applied 2.5 sec after the onset of the maintenance period. At the end of each trial, participants were asked to judge the test cue contrast relative to VSTM/imagery content (i.e. is the test cue of lower or higher contrast). The timeline on the left presents the assessment of memory cue. The timeline on the right shows the assessment of imagery cue.

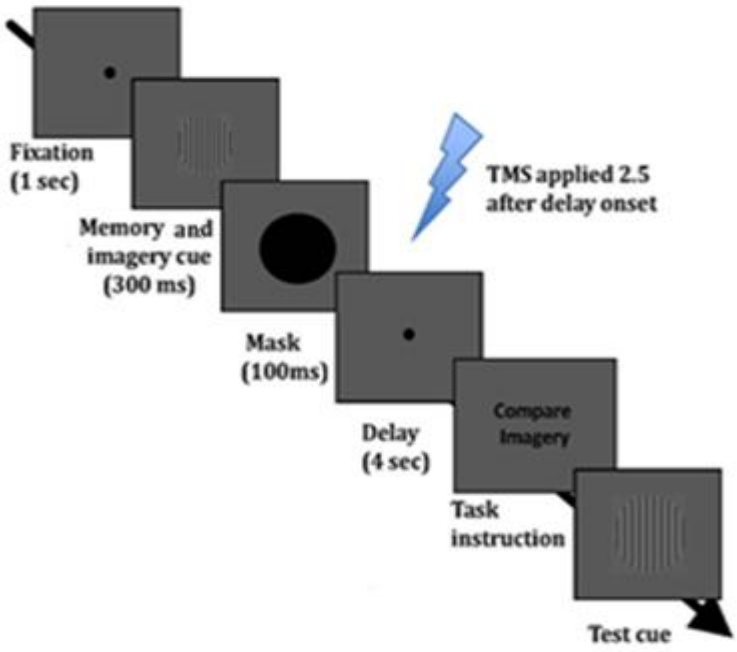

Fig.13 Timeline of the second experiment. At the start of each trial, participants were presented with a cue. The task involved maintaining the contrast of the grating by holding it in memory and simultaneously forming a conscious mental image of it and maintaining it throughout the maintenance period. TMS pulse train was applied 2.5 sec after the onset of the maintenance period. After the delay participants were informed either memory for the original memory cue would be assessed, or they should perform the contrast discrimination task relative to their conscious mental image.

5.5 GENERAL PROCEDURE

Prior to experiment 1 participants were instructed either to hold the cue in memory (VSTM condition) (Silvanto and Soto, 2011) or to form a mental image of the cue (imagery condition) (Keogh and Pearson, 2011; Slotnick et al., 2012; D'anguilli et al., 2013). At the very beginning of the experiment subject were presented with a fixation point to focus their attention at the center of the

monitor, which lasted for 1 second. Afterwards the main cue which is a contrast grating was displayed for 300ms and the task for the subjects was to keep it in memory or/and to form mental image. The Michelson contrast of the memory/imagery cue was either 0.2, 0.3, 0.4, or 0.5, and was always vertical. The mask (black circle) was presented to participants for 100ms to avoid any afterimage. The next step of the procedure was the delay of 4seconds during which TMS train pulse was executed after 2.5 seconds. At the end of the trial, every participants had to assess whether the test cue presented at the end had lower (press 1) or higher (press 2) contrast in comparison to their own memory or imagery of the cue.

5.6 TMS STIMULATION AND SITE LOCALIZATION

rTMS biphasic pulses were delivered using a Magstim rapid2 (Magstim super Rapid Plus, Magstim company, UK) using a figure-of-eight 70-mm aired cooled coil. The coil was held using a custom-made magic-arm and placed tangentially on the skull. There were nine participants who did not perceive phosphenes during experiment. For this group the the TMS coil was placed 2 cm above the inion and 0.5 cm laterally on the right hemisphere (Campana et al, 2002). For subjects who perceived phospehnes, the coil position was slightly moved from the original coordinates (Pascual-Leone and Walsh, 2001). For Sham TMS, the coil with foam was placed 2cm above the central parieto-occipital (POz) region**.** Before the experiment, every participant had his phosphene threshold specified. The calculation was made via modified binary search paradigm (MOBS, Tyrrell & Owens, 1988). During each session, phosphene was not reported by any of the subjects. Half of the participant had their MRI scans, which helped in more precise placement of TMS coil in the vicinity of the

calcarine sulcus via the neuro-navigation system. Pulse train consisting of five pulses was applied at 10 Hz (Ashbrige et al, 1997; Campana et al, 2002, 2006; Muggleton et al, 2003; Saad and Silvanto; 2013a). In order to allow the production of undisturbed generation of mental image as well as to avoid the risks of train pulse overlapping with test cues there was a need to establish a proper time window in the course of this experimental procedure. Therefore TMS was applied at 2.5 sec of the maintenance. In first experiment, each of the 4 conditions (EVC TMS-VSTM; EVC TMS-Imagery; Sham TMS-VSTM; Sham TMS-Imagery) was run in a unique block of 32 trials. In second experiment each of the 2 conditions (Mixed EVC-TMS; Mixed Sham-TMS) was run in 2 blocks each of 32 trials.

5.7 QUESTIONNARE ASSESSING TASK STRATEGY

The final phase of the experiment was the questionnaire which helped inquiring subjects' cognitive strategies.

The questions were as follows: For VSTM: "Please describe in detail how you memorized the original cue; what strategy or process did you follow until asked to judge your memory of the cue"

For imagery: "Please describe in detail how you formed the mental image and what strategy or process did you follow until asked to judge your image of the cue?"

For Condition 3: "Where you able to memorize and make a mental image of the main cue? Please describe in detail how you memorized the memory/imagery cue and made a mental image of it; what mental strategy or process did you follow until asked to judge your memory/imagery of the cue? "

The outcome of the provided questionnaire resulted in exclusion of five participants. According to their answers, two of subjects were using improper maintenance process, which resulted in not using imagery when it was required. Another three participants used the same maintenance process in every session they took part in. The rest of the participants (n=18) reported having followed task instructions.

6. Results

6.1 OVERALL EFFECTS OF VSTM AND IMAGERY ON SENSITIVITY

Figure 14 and figure 15 shows the mean (n=18) sensitivity (d´) for VSTM and imagery as a function of TMS site and difficulty level. Initially an ANOVA was carried out into which all independent variables were entered. This 2x2x2x2 ANOVA, with task (imagery or VSTM), condition type (alone or concurrent), TMS site (EVC or sham), and difficulty (easy or difficult) revealed a main effect of difficulty ($F(1,14) = 59.32$; $p < 0.001$), and a 2-way interaction between condition type and TMS ($F(1,14) = 11.06$; $p = 0.005$). None of the other main effects or interactions was significant.

The post-hoc comparisons were carried out. In these t-tests we collated the data across tasks (Imagery, VTSM) and the difficulty levels (easy or difficult) as neither factor was involved in significant interactions in the ANOVA. These pairwise comparisons revealed that, in the alone condition, EVC-TMS enhanced the sensitivity relative to sham ($t(17) = -4.43$; $p < 0.000$); in contrast, in the concurrent session, EVC-TMS did not modulated the sensitivity relative to sham ($t(17) = 0.24$; $p = 0.81$).

To check if baseline performances of the tasks were modified across condition type we conducted a 2x2x2 ANOVA in which we entered condition type (alone or mixed), task (VSTM or imagery), and difficulty level as independent variable. This revealed a significant effect of difficulty level ($F(1,14) = 14.08$; $p = 0.002$). However, no other main effect or interaction was significant effect was found (highest p-value 0.35).

In summary, EVC-TMS enhanced the sensitivity of both VSTM and imagery when conducted separately. In contrast, TMS had no impact on sensitivity in the mixed condition. The baseline performance level of imagery and VSTM did not differ, and was not modulated by the task (i.e. alone or concurrent).

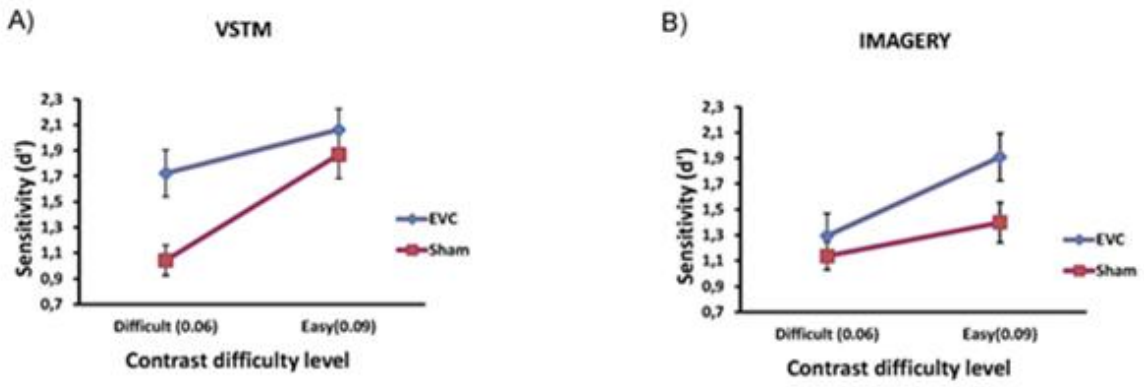

Fig. 14 A) VSTM condition. B) Imagery condition. Graphs present sensitivity (d') as a function of TMS site and contrast difficulty level (mean n=18). Notice: for sensitivity error bars indicate +/- SEM from which between-subjects variance has been removed.

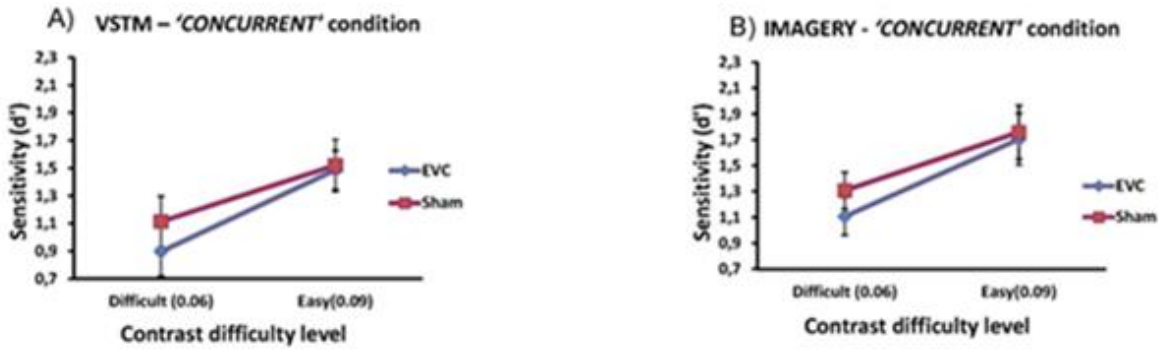

Fig.15 A) VSTM concurrent condition. B) Imagery concurrent condition. Graphs present sensitivity (d') as a function of TMS site and contrast difficulty level (mean n=18). Notice: for sensitivity error bars indicate +/- SEM from which between-subjects variance has been removed.

6.2 OVERALL EFFECTS OF TMS ON REACTION TIME

Three participants were removed due to performances of 3SD above the mean; therefore the reaction times analysis was conducted on 15 participants. Figure 16 and figure 17 shows the mean (n=15) median reaction time during VSTM and imagery conditions as a function of TMS site and contrast difficulty level.

We initially carried out an ANOVA into which all independent variables were entered. This 2x2x2x2 ANOVA, with task (imagery or VSTM), condition type (alone or concurrent), TMS site (EVC or sham), and contrast difficulty (easy or difficult) revealed a main effect of condition type ($F(1,13) = 26.61$; $p < 0.001$), difficulty level ($F(1,13) = 17.50$; $p = 0.001$), a 2-way interactions between Task and TMS site ($F(1,13) = 9.5$; $p = 0.009$), and a 2-way interactions between difficulty level and TMS site ($F(1,13) = 8.64$; $p = 0.01$). None of the other main effects or interactions were significant.

As task was interacting with TMS site, we conducted separate ANOVAs for each task selectively in order to investigate these effects. For VSTM, we conducted a

2x2x2 ANOVA with condition type (alone or concurrent), TMS site (EVC or sham), and contrast difficulty (easy or difficult). This revealed a main effect of condition type ($F(1,13) = 26.4$; $p < 0.001$), difficulty level ($F(1,13) = 5.8$; $p = 0.031$), and TMS site ($F(1,13) = 9.23$; $p = 0.009$). None of the interactions were significant. The main effect of TMS indicates that TMS induced a slowing down of RTs for VSTM.

For imagery, we conducted a 2x2x2 ANOVA with condition type (alone or concurrent), TMS site (EVC or sham), and contrast difficulty (easy or difficult). This revealed only a main effect of condition type ($F(1,14) = 28.5$; $p < 0.001$). None of the other interactions were significant. Thus TMS had no effect on RTs for imagery.

In sum, these results show that TMS applied at EVC increased reaction times relative to Sham in the VSTM task. No such effect was found for imagery.

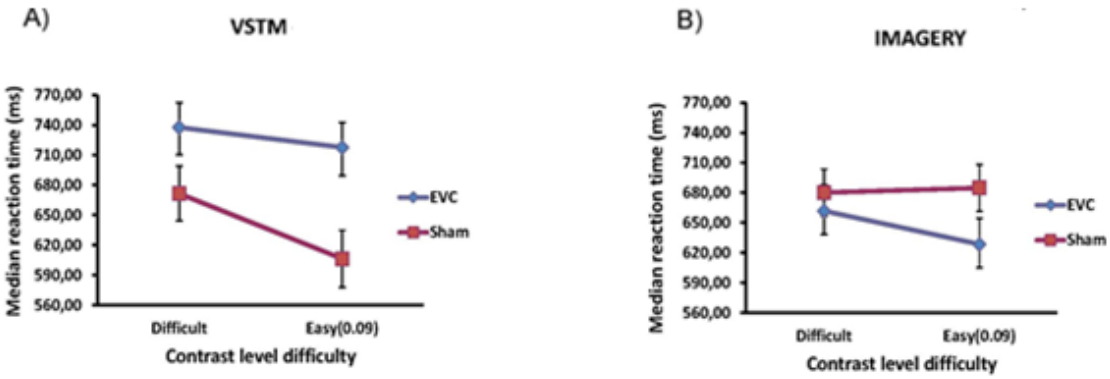

Fig.16 A) VSTM condition. B) Imagery condition. Graphs show median reaction time (ms) as a function of TMS site versus contrast difficulty level (mean n=15) for VSTM and imagery. Notice: reaction time the Error bars indicate SDs from which between-subjects variance has been removed (Loftus and Masson, 1994).

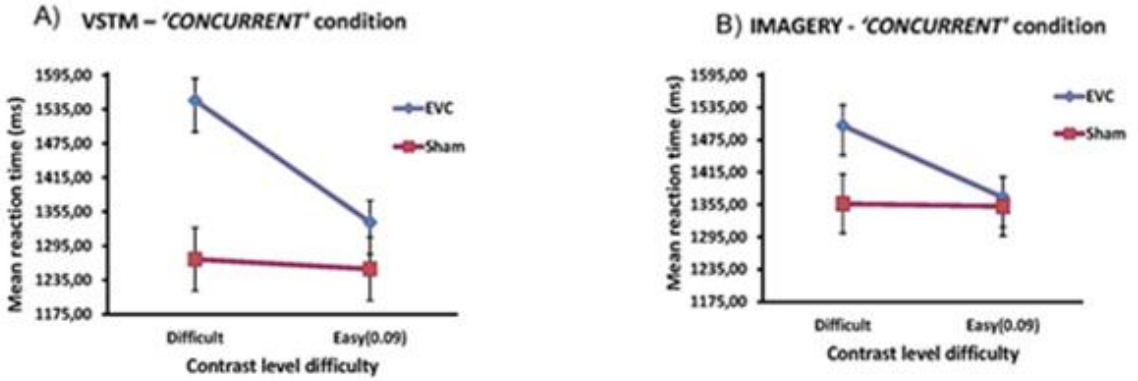

Fig.17 A) VSTM concurrent condition. B) Imagery concurrent condition. Graphs show median reaction time (ms) as a function of TMS site versus contrast difficulty level (mean n=15) for concurrent VSTM and concurrent imagery. Notice: for reaction time the Error bars indicate SDs from which between-subjects variance has been removed (Loftus and Masson, 1994).

7. Discussion

The aim of this study was to see if TMS applied at the EVC will dissociate visual short term memory and imagery neural bases.

TMS applied over the early visual cortex during VSTM alone condition increased the sensitivity of VSTM and the reaction time in both alone and simultaneous experiments. During the imagery alone condition, TMS stimulation also increased the sensitivity of imagery. However, there was no influence on the reaction time. The sensitivity enhancement found during experiment 1 is coherent with previous finding done by Kosslyn et al. (2006) and Cattaneo et al. (2009). In experiment 2 VSTM and imagery condition, TMS pulses had not effect on the sensitivity of participants.

How can these differential effects are explained. Sensitivity is a measure based on the accuracy recall, it therefore represents the inspection of the mental representation, in other words how clear and accurate my representation of the main cue is. The reaction time measure reflects the time that is required in order to reach these representations.

thus whereas mental imagery is a process requiring continuous update and effort to keep hold of the image, VSTM retention requires less efforts. In line with the state decency theory (Silvanto et al., 2007), the state of the neuronal population implicated in the RT for VSTM were less active compared to the mental imagery one and thus susceptible to TMS.

In summary, we indicated that TMS had a differential impact on the reaction times of VSTM and imagery, dissociating these processes at the level of the early visual cortex. While the current literature often emphasizes the visual cortical overlap in neural resources for VSTM and imagery, our study demonstrates that differences between these two cognitive functions exist at the level of the visual representations.

What can be concluded from the results is that imagery and VSTM were differentially affected by TMS, demonstrating that their neural bases do differ at the level of early visual cortex. The specific nature of these differences requires further study.

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