Investigation of the segregated visual system

Ph.D. Thesis

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Publications

Papers related to the thesis

I. Kaposvari P , Csete G , Bognar A , Csibri P , Toth E , Szabo N , Vecsei L , Sary G , Tamas Kincses Z
Audio-visual integration through the parallel visual pathways.
BRAIN RESEARCH 1624: pp. 71-77. (2015), IF: 2.561

II. Csete G , Bognar A , Csibri P , Kaposvari P , Sary G
Aging alters visual processing of objects and shapes in inferotemporal cortex in monkeys.
BRAIN RESEARCH BULLETIN 110C: pp. 76-83. (2015), IF: 2.572

III. Csete G , Szabo N , Rokszin A , Toth E , Braunitzer G , Benedek G , Vecsei L , Tamas Kincses Z
An investigation of the white matter microstructure in motion detection using diffusion MRI.
BRAIN RESEARCH 1570: pp. 35-42. (2014), IF: 2.843

Papers not directly related to the thesis

I. Kiraly A, Szabo N, Toth E, Csete G, Farago P, Kocsis K, Must A, Vecsei L, Kincses ZT.
Male brain ages faster: the age and gender dependence of subcortical volumes
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V. Kaposvári P , Csibri P , Csete G , Tompa T , Sáry G
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Introduction

Most of our information from the outer world is gained by vision. An intact visual system is crucial for life and for the optimal recognition. For correct explanation and interpretation of discrepancies caused by certain diseases, the thorough knowledge of the visual system is substantial. It also helps to understand the human development better and helps to identify improved biomarkers for diagnosis and treatment. For the facilitation of these opportunities, it is important to investigate the whole system from the neural level to the global, the network level.

The light after reflection from the objects passes through the lens and cornea to the retina where the fototransduction takes place. After the primary processing, the information of the ganglion cells is sent to the lateral geniculate body (LGB). Three functionally distinct subtypes of ganglion cells, such as the magnocellular (M), the parvocellular (P) (and koniocellular (K)[1]) neurons are located here. M-cells respond to moving stimuli, speed and location in space and show great sensitivity to low contrast. On the other hand, P-cells prefer colours, shape and higher spatial frequencies (Skottun, 2015). The fibres project to the calcarine sulcus via the optic radiation. In the occipital pole, the information from the retina is mapped point by point. Fibres from the retina keep their relative positions to each other, serving retinotopic organization. The axon bundles from the parvocellular and magnocellular system remain separated at this level and reach different layers of the primary visual cortex. The occipital cortex has a large amount of internal granular cells with myelinated axons that cause a distinctive stripe in the cerebral cortex that are called lines of Gennari (Gennari, 1782). V1 is built by orientation columns, “blob”-s and ocular dominance columns. All together it is a virtual neuron-cube, called hypercolumn (Hubel and Wiesel, 1968), that dissociates the detected image on the retina into small building elements, or features (e.g. lines, colours, orientation).

From the primary visual cortex the visual information is passing through two major pathways, to the parietal lobe and to the temporal lobe: the so-called dorsal and ventral

[1] The koniocellular system is not the main target of our investigations; hence no further details are given.

pathways, respectively, traditionally regarded as the ’where’ and the ’what’ stream (Haxby et al., 1991; Ungerleider and Haxby, 1994). Two relevant processing stages should be mentioned as presumably final unimodal stages of the segregated streams as the middle-temporal (MT) and the inferior-temporal cortex (IT).

The region MT is sensitive to movement, depth and activated during visuo-spatial tasks. Higher levels of perception, such as global motion recognition seems to be located in the middle temporal area (MT), medial superior temporal cortex (MST), and the fundus of the superior temporal cortex (FST), that share similar features in monkeys and humans (Morrone et al., 2000), and was suggested to make up a complex: V5/MT+ (Boussaoud et al., 1990; Morrone et al., 2000). This area receives direct input from the primary visual cortex (V1) (Felleman and Van Essen, 1991; Maunsell and van Essen, 1983), LGN (Sincich et al., 2004), and also extrastriate regions, such as V2 (Lewis and Van Essen, 2000). These neurons with a broadly binocular representation and a relatively large receptive field ((~15-20°,(Angelucci et al., 2002), have a principal role in motion and directional sensitivity (Chawla et al., 1998).

The IT is the last unimodal area in the ventral visual stream (Ungerleider, 1982) which receives the visual input mostly from areas V4 and the posterior part of the IT (TEO,(Baleydier and Morel, 1992; Merigan, 1996; Morel and Bullier, 1990). Receptive field of these cells span about 50-60° and contains binocular representation of the sighted world. Cells in the IT respond best to complex, colourful stimuli (Desimone et al., 1984). They might be selective to shapes, i.e., they respond to, or rather respond more strongly to some shapes than to others (Desimone et al., 1984; Gross et al., 1972; Tanaka et al., 1991) and show strong invariance against certain modifications (Sáry et al, 1993). The IT is closely associated to perception. Micro-stimulation of the area influences the face non-face categorization (Afraz et al., 2006), and human perception models show similar cell firing patterns as IT neurons (Allred et al., 2005). Furthermore, the use of the binocular rivalry paradigm (Leopold and Logothetis, 1996; Sheinberg and Logothetis, 1997) proves that visual perception and IT activity are closely related.

Objectives

The aim of our studies was to examine the visual system on different levels with alternative methodologies. The following specific questions were addressed:

- How does the neural coding of visual stimuli changes with ageing?
- What is the white matter structural background of the motion detection?
- Could the segregated visual pathways be identified in a double flash illusion experiment?

Aging alters visual processing of objects and shapes in inferotemporal cortex in monkeys

Cognitive functions, including visual perception, decline with age. This deterioration of the perceptual processes can be attributed not only to optical defects such as cataract, glaucoma or presbyopia, but also to neurological aging and dysfunction in visual areas. This may have a major impact on the occurrence of home accidents, automobile driving and the quality of life in general (Carter et al., 1997; Desapriya et al., 2014; Kallstrand-Eriksson et al., 2013). Data from psychophysical studies indicate that older people tend to have decreased visual acuity, contrast sensitivity and contour integration (Hutman and Sekuler, 1980; Roudaia et al., 2008; Sekuler et al., 1980). They often demonstrate impairments in visual motion sensitivity, including the perception of apparent motion, and have poorer orientation-judging capabilities (Bennett et al., 2007; Betts et al., 2007; Roudaia et al., 2010)(for a review, see (Andersen, 2012). It has been reported that aging also has an impact on form perception and shape discrimination (Habak et al., 2009; McKendrick et al., 2010; Weymouth and McKendrick, 2012) and figure-background separation (Chee et al., 2006), but it is not clear what changes accompany these impairments.

A number of papers have addressed the connection between aging and the decline of visual functions (Liang et al., 2010; Schmolesky et al., 2000; Spear, 1993; Wang et al., 2006; Wang, 2001; Yang et al., 2008; Yang et al., 2009; Yu et al., 2006), but we are not aware of any electrophysiological report concerning the effects of aging on the neuronal activity underlying object and shape vision in a high-level visual area such as the monkey inferotemporal cortex (IT).

Methods

We compared data obtained from single-cell recordings from monkeys in two age groups: 7 years and 27-33 years (corresponding to 21 and 81-99 years, respectively, in humans).

All the participating animals (*Macaca mulatta*) were engaged in earlier studies in the visual laboratory. The animals performed a simple fixation task and were exposed to the same set of images at a certain stage during their training (for an example of the stimulus set, see (Sary et al., 2006). To compensate for implicit learning, we took our sample from a later phase of the experiments, when the animals could be regarded as experienced or even overtrained. Our behavioural threshold was set to 87%, but at the time of the recording all the animals performed at > 90% correct level.

The four monkeys that participated in the study weighted between 6 and 9 kg at the time of the experiments. In the young group, the two monkeys were males and the old animals were 2 females. Prior to their training, the animals underwent two session of aseptic surgery. A stainless steel headpost was fixed to the head to keep the animal's head stable, and a search coil was implanted under the conjunctiva (Judge et al., 1980) to enable recording of the eye position.

The animals performed a fixation task. First, a red fixation point was presented on the monitor (distance: 57 cm) for 500 ms, followed by a gray background (500 ms) and then by the stimulus (500 ms). For each cell, 20 stimuli were used, showing colour reproductions of real world 3D objects or geometric shapes (Sáry et al., 2004). For each of the stimuli at least 10 successful trials (and recordings) were collected in a semi-random fashion. Trials were considered successful if the animal did not break fixation during the trial (fixation window ~ 0.5˚). Trials were machine paced; the inter-trial interval was set to 1 s. This way, collecting all the required responses lasted for about 7-8 minutes per cell, depending on the number of unfinished trials. Only correct trials were included in the analysis. The neuronal activity from the IT was recorded by using standard electrophysiological methods. Cellular activity was analyzed off-line. All procedures used during surgery and training of the animals conformed fully to the NIH standards and had been approved in advance by the Ethical Council of the University of Szeged.

Results

We recorded a total of 288 neurons from 4 *Macaca mulatta* monkeys to investigate the functional consequences of neuronal aging. Two groups of data were formed for comparison: a young group ("Young", 2 monkeys, aged 7 years, number of cells: 221) and an old group ("Old", 2 monkeys aged 27 and 33 years, respectively, number of cells: 67).

We compared the data on all the registered cells by means of the Mann-Whitney U test. The baseline of firing rate did not significantly differ in the 2 groups: 6.00 (2.81 - 9.69) spikes/s in the Young, and 5.23 (2.50 - 10.27) spikes/s in the Old animals, respectively.
The evoked-to-spontaneous ratio was 3.63 (2.19 - 6.10) in the Young and 3.26 (2.34 - 6.75) in the Old group. Once again, there was no significant difference between the groups.
The Fano-factor did not indicate differences between the groups either: 1.26 (0.76 - 1.85) and 1.31 (0.84 - 2.00) for the Young and Old groups, respectively.
The net firing rates were likewise not different: 15.67 (8.33 - 25.33) spikes/s vs. 14.33 (8.33 - 24.66) spikes/s, respectively, in the Young-Old comparison.
On the other hand, the latency revealed a difference between the Young and Old groups (Table 1): 128.73 (96.88 - 161.86) ms and 147.20 (124.54 - 179.83) ms, respectively; U= 4101.00; $p_{corr}< 0.05$.
SI too demonstrated a difference (U = 4810.50; $p_{corr}< 0.001$) in the Young vs. Old comparison : 0.89 (0.69 - 0.97) and 0.76 (0.47 - 0.90), respectively.
The SP values for the Young-Old groups (Table 1) were (0.47 (0.28 - 0.73) and 0.75 (0.56 - 0.90), respectively), this difference was significant, according to the Mann-Whitney test (U = 4245.50; $p_{corr}< 0.001$).
DSI similarly pointed to a group difference in the Young-Old comparison: (0.60 (0.44 - 0.79) vs. 0.46 (0.31 - 0.68), respectively; U= 5197.00; $p_{corr}< 0.01$).

To reduce the biasing effects of unequal samples, we repeated the analysis on 22 randomly chosen cells from each animal, i.e., 44 cells from each age group. Cells were selected from that stage of the experiments when the animals were considered overtrained. During this phase, the animals worked on a daily basis, achieving a > 90 % performance rate in the task, and the effect of attentional fluctuation could therefore be minimized.
As in the analysis involving all the cells, the response latency values of the Young and Old data were statistically different: 124.85 (97.00 - 161.74) ms and 154.51 (129.33 - 178.64) ms, respectively (U = 567.00; $p_{corr}< 0.01$). Also, the SI values pointed to a significant difference between the groups (U = 713.50; $p< 0.034$) before the Bonferroni correction, which disappeared after it ($p_{corr}< 0.27$). Since in our opinion, this difference is essential for understanding neuronal aging and the decrease in perceptual performance, we rerun this comparison with the Monte - Carlo method in addition to the Bonferroni

correction ($p_{permutation}$< 0.027). The neuronal selectivity values in the two groups were: 0.90 (0.69 - 0.97) vs. 0.81 (0.51 - 0.92). As for the DSI values, the same procedure masked the result (U = 670.00; p < 0.013, p_{corr} < 0.10). However, after randomization, the differences were significant (<0.02).

The SP parameters, were significantly different (U = 587.00; p_{corr}< 0.05): 0.46 (0.29 - 0.73) vs. 0.75 (0.51 - 0.88), in the Young and Old groups, respectively.

An investigation of the white matter microstructure in motion detection using diffusion MRI

The neural substrates of motion sensitivity are located at different levels of the visual system. Electrophysiological investigations have revealed that in the retina subgroups of ganglion cells react differently to moving lights, some responding with activation and others with decreased firing (Sivyer et al., 2010). Similarly, the lateral geniculate nucleus (LGN) (Stanley et al., 2012), the striate cortex (Beckett et al., 2012) and some peri- and parastriate areas (Larsson et al., 2010; Sary et al., 1995) respond to a dot moving across the receptive fields of the neurons. Higher stages are presented in the area of V5/hMT+ (Boussaoud et al., 1990; Morrone et al., 2000), which participates in motion and depth perception, eye-movements, detection of speed, computing pattern motion, integrating direction of motion (Born and Bradley, 2005) in spatial properties processing (Lui and Rosa, 2015) and extracting structure from motion (Siegel and Andersen, 1988).

Most of the available information on the V5/MT+ originates from monkey experiments, human fMRI and positron emission tomography (PET) studies. Such knowledge is mostly functional in nature, but the structural background of motion detection is not sufficiently well known, especially that regarding the white matter pathways.

Methods

Subjects

Sixteen healthy volunteer subjects (average age was 26.5 (range: 21-40 years); 9 female, 11 right-handed, mean body mass index = 22.05 ± 4.22) participated in the study. None of them suffered from any neurological or psychiatric diseases. All subjects had normal or corrected-to-normal (5/5) visual acuity.

Ethics

All study participants provided their written informed consent in accordance with the Declaration of Helsinki; the study was approved by the ethics committee at the University of Szeged (Ref. no.: 87/2009).

Psychophysical test

The motion detection threshold was measured with a random-dot kinematogram. Stimuli were generated with Psychophysics Toolbox Version 3 (http://psychtoolbox.org/), under Matlab (The MathWorks, Inc.) on a PC, and presented on a 24-inch LCD monitor at a resolution of 1920 by 1200 pixels and at a 60 Hz refresh rate. The stimuli were 100 moving black dots in random positions with variable coherence rates. Stimuli were presented on a neutral grey background in a rectangular stimulation field occupying 60% of the whole screen. Subjects were seated at 0.5 m from the screen and the stimulation field subtended an area of 35.74 by 22.34 visual angles. The diameter of each dot was 10 pixels (~ 3 mm). In each trial, a given percentage of the dots moved coherently to the right or to the left, while the remainder moved in random directions. After each trial, movement-starting points were generated *de novo*. One trial lasted approximately for 0.8 s (50 consecutive frames), during which each dot travelled a distance of 38.4 mm. (For more details see: (Braunitzer et al., 2012)). The task of the subjects was to indicate whether the coherently moving dots moved to the left or to the right by pressing the appropriate cursor button on the keyboard. The absolute coherence threshold was determined by the QUEST adaptive threshold-seeking algorithm (Watson and Pelli, 1983).

Data acquisition:

Neuroimaging data acquisitions were carried out on a 1.5 T GE Signa Excite HDxt MR Scanner (GE Healthcare, Chalfont St. Giles, UK). Three-dimensional spoiled gradient echo images (FSPGR: echo time [TE]: 4.1 ms; repetition time [TR]: 10.276 ms; matrix: 256 * 256; field of view [FOV]: 25 cm * 25 cm; flip angle: 15 degrees; in-plane resolution: 1 mm * 1 mm; slice thickness: 1 mm) and 60-direction diffusion-weighted images with 6 non-diffusion-weighted reference volumes (TE: 93.8 ms; TR: 16.000 ms; matrix: 96 * 96; FOV: 23 cm * 23 cm; flip angle: 90 degrees; in-plane resolution: 2.4 mm * 2.4 mm; slice thickness: 2.4 mm; b: 1000 s/mm^2; number of excitations [NEX]: 2; array spatial sensitivity encoding technique [ASSET]) were acquired for all subjects.

Data analysis:

Correlation of diffusion parameters with behavioural measures

Diffusion data were corrected for eddy currents and movement artefacts by 12 degree of freedom affine linear registration to the first non-diffusion-weighted reference image. An algorithm included in the FMRIB Diffusion Toolbox (FDT) of FSL (v.4.0) fitted diffusion tensors at each voxel (Smith et al., 2004). The FA was computed for the whole brain. In order to reduce the possible errors arising from misalignment of the images, we used the Tract Based Spatial Statistics (TBSS) method (Smith et al., 2007). The FA images for all subjects were aligned into a common space with the non-linear registration tool FNIRT, which uses a b-spline representation of the registration warp field. A mean FA image was created and the threshold was set at FA=0.2, yielding a mean FA skeleton at the centres of all tracts common to the group. The aligned FA data for each subject were then projected onto this skeleton and the resulting data were fed into voxel-wise cross-subject statistics. Modelling and inference by using the standard general linear model (GLM) design set-up was accomplished by using permutation-based cluster analysis (n=5000) as implemented in the FSL software package (Nichols and Holmes, 2002). The design was encoded for the motion detection threshold value. Statistical thresholding was carried out with a novel method of Threshold Free Cluster Enhancing (Smith and Nichols, 2009). Since a correlation was expected only in well-circumscribed regions of the visual and attention networks, it would have been over-conservative to correct for multiple correlations based on the total number of voxels in the skeleton. Hence, we used the non-corrected statistics thresholded at the 1% significance level. Only clusters larger than 4 voxels were considered for further analysis and discussion.

Structural connectivity

Connectivity of the regions showing a significant correlation with the motion detection threshold was defined by probabilistic tractography (FDT, part of FSL: www.fmrib.ox.ac.uk/fsl/fdt). A multifibre diffusion model was fitted that estimated the probability distribution in the direction of 1 or more fibre populations at each voxel (Behrens et al., 2007). Probabilistic tractography was then performed from any brain voxel by tracing streamline samples through these probabilistic distributions in the fibre direction. For tractography, we generated 5000 streamline samples from each seed voxel to build up a connectivity distribution. The number of these samples passing through each brain voxel was interpreted as proportional to the probability of connection to the seed

voxel. By fitting a multifibre model to our diffusion data, we were able to trace pathways through regions of fibre crossing (Behrens et al., 2007). The seed masks were the binary masks of the suprathreshold clusters of the TBSS analysis. The result of the tractography was registered to standard space, binarised and summed over subjects for visualisation.

Results

Correlation of the white matter integrity and the motion detection threshold

The mean motion detection threshold was 18.87 ± 5.79 % coherent motions. A significant positive correlation was found between the motion detection threshold and the local FA in the right frontal cortex in the posterior part of the right superior frontal gyrus ($p<0.0032$, non-corrected), the right juxta-cortical superior parietal lobule ($p<0.0032$, non-corrected), the left parietal white matter ($p<0.001$, non-corrected), the left superior temporal gyrus ($p<0.0026$, non-corrected) and the left optic radiation ($p<0.0036$, non-corrected).

Connectivity of the white matter region having correlated microstructure with behavioural data

The right frontal cluster showed strong connections to the identical region in the left hemisphere and to the right cortico-spinal tract, and a smaller pathway leading to the right parietal lobe. The right superior parietal cluster exhibited the strongest connectivity to the right superior temporal gyrus. The cluster in the left parietal white matter had strong connections to the angular gyrus, the frontal white matter (through the putative superior longitudinal fascicle) and the occipito-temporal junction. The cluster in the superior temporal gyrus had connections to the angular gyrus, which led further to the frontal cortex through the arcuate fascicle, and a smaller fibre tract connected the cluster to the parietal white matter under the precuneus.

Audio-visual integration through the parallel visual pathways

One brief flash and two short tones presented simultaneously induce the illusion of a second flash, called the double flash illusion. Since the first description of the phenomenon (Wilson, 1987), there have been several studies of the possible background mechanisms. Event-related potential studies demonstrated that auditory stimuli could influence the activity of the visual cortex (Shams et al., 2001; Teder-Salejarvi et al., 2002)

and an illusory flash-related gamma burst was found in primary visual areas (Bhattacharya et al., 2002; Mishra et al., 2007). Functional MRI investigations revealed illusory flash-related brain activity in the superior colliculus, the primary visual cortex, and the right superior temporal sulcus (STS) (Watkins et al., 2006). These findings suggest that such interaction of the bimodal information could be based on the communication between the primary visual cortex, the STS and the primary auditory cortex (Mishra et al., 2007; Watkins et al., 2006; Watkins et al., 2007). Earlier studies suggested that the double flash illusion is primarily mediated by the dorsal pathway. However, it has not yet been investigated whether the phenomenon can be evoked over both visual streams, and no systematic investigation of the involved neural structures of the dorsal and ventral streams in the illusion has yet been performed. The segregated visual pathways can easily be distinguished by modulating the contrast of the stimuli: stimuli with high contrast and colour are processed predominantly in the ventral stream, while stimuli with low contrast are processed in the dorsal stream (Brannan and Bodis-Wollner, 1991; Legge, 1978).

Methods

Sixteen healthy subjects (10 females; mean age of 27.4 years) were enrolled in the study. None of them suffered from any neurological or psychiatric diseases. All of them had normal or corrected-to-normal (5/5) visual acuity and good colour vision.

Two conditions were investigated: an isoluminant (IL) condition, where a red disc was presented on a green background (8.9 cd/m2), and a low-contrast (LC) condition, where we used a light-grey disc (9.7 cd/m2, contrast 9%) on a darker grey background (8.9 cd/m^2). The conditions were presented in a semi-random sequence.

The conditions contained 6 subconditions: 6 variations of flashes (one flash, one flash with one tone, one flash with two tones, two flashes, two flashes with one tone, and two flashes with two tones). One subcondition consisted of 40 repetitions of the trial, and thus one block contained 240 semi-random-presented trials.

Neuroimaging data acquisition and data analysis was following the same algorithm as previously mentioned.

Results

Behavioural data

The paired t-test between d' values, given by using Signal Detection Theory, in control and double-flash conditions indicated significant results in both the low contrast (LC) condition ($p < 0.0003$) and the isoluminant (IL) condition ($p < 0.0027$).

The criterion revealed significant ($p < 0.01$) negative bias for the double flash as compared with the control criterion in both conditions (Table 1). This shows that two tones biased the participants to report two flashes instead of one for double-flash illusions, but not the general response bias.

Correlation of behavioural data with white matter microstructural integration

In the IL condition, a significant positive correlation of the behavioural data (the likelihood of perceiving a double-flash illusion) and the fractional anisotropy (FA) was found in the juxtacortical infero-temporal white matter on the right and in the bilateral insulae by the Tract-Based Spatial Statistic (TBSS) analysis.

In the LC condition, a significant positive correlation was observed between FA and the likelihood of perceiving a double-flash illusion in the juxtacortical white matter of the parieto-occipital junction on the right side, the right frontal white matter under the superior frontal gyrus and bilaterally in the deep cerebellar white matter.

Connectivity analysis

The probabilistic tractography from the infero-temporal white matter region revealed a high correlation with the likelihood of perceiving a double-flash illusion in the IL condition, showed tracks running along the inferior border of the temporal lobe through the inferior fronto-occipital fascicle and the inferior longitudinal fascicle.

In the LC condition, the tractography initiated from the juxtacortical parieto-occipital cluster of the TBSS analysis showed fibres along the putative arcuate fascicle, running towards the frontal lobe.

Discussion

In our three consecutive investigations the visual system was examined starting from neuronal level using single-unit recording up to the whole brain network interaction by diffusion tractography. This thesis report aims to investigate two main fields. First, the structural determinants of behaviour and second, the deterioration of the neuronal response by ageing.

Macaque monkeys have been a widely used animal model to study human visual perception. Several papers have compared the homology to humans; the investigation of changes in the shape representation of the monkey IT may therefore facilitate an understanding of age-related changes in the human visual system. In this animal experiment, we have reported an aging related increase in response latency and a worsening of the stimulus selectivity in awake, behaving monkeys.

The investigation of motion detection revealed local correlations between the white matter microstructure parameters measured by diffusion MRI and the coherent motion detection performance in several regions that can be linked to motion detection and attention functions. Examining the white matter background of motion detection, we revealed the main components of the attention networks that are related to the random-dot kinematogram paradigm. Similarly, this study highlights the importance of the structural determinants of perception. Hopefully, the presented results promote to apprehend the processing of motion detection, and, in general, the visual sensation, and in future all together assist to better representation and interpretation of attention-related alteration in several diseases.

In the experiment of audio-visual integration, we evoked a robust double-flash illusion through the dorsal and ventral visual streams. Correlation was observed between the white matter microstructure parameters and the likelihood of perceiving double-flash illusion using stimuli parameter preferred by the segregated visuals streams that suggest the fact that audio-visual integration involves both systems. Up to our knowledge, this is the first study that showed the white matter microstructural background of the segregated, the so-called ‘What’ and ‘Where’ visual pathways.

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