2021 43rd Annual International Conference of the
IEEE Engineering in Medicine & Biology Society (EMBC)
Oct 31 - Nov 4, 2021. Virtual Conference

RoMAT: Robot for Multisensory Analysis and Testing of visual-tactile perceptual functions

Monica Gori[1a], Marco Crepaldi[1b], Lorenzo Orciari[1c], Claudio Campus[1a], Andrea Merello[1b], Davide Dellepiane[1b], Alberto Parmiggiani[1c]

***Abstract*— The present work aims to introduce a novel robotic platform suitable for investigating perception in multi-sensory motion tasks for individuals with and without sensory and motor disabilities. The system, called RoMAT, allows the study of how multisensory signals are integrated, taking into account the speed and direction of the stimuli. It is a robotic platform composed of a visual and tactile wheel mounted on two routable plates to be moved under the finger and the visual observation of the participants. We validated the system by implementing a rotation discrimination task considering two different sensory modalities: vision, touch and multisensory visual-tactile integration. Four healthy subjects were asked to report the length of motion rotation after perceiving a moving stimulus generated by the visual, tactile, or both stimuli. Results suggest that multisensory precision improves when multiple sensory stimulations are presented. The new system can therefore provide fundamental inputs in determining the perceptual principles of motion processing. Therefore, this device can be a potential system to design screening and rehabilitation protocols based on neuroscientific findings to be used in individuals with visual and motor impairments.**

***Clinical relevance*— This research presents a novel robotic motion simulator to deliver combined or independent stimulation of the visual and tactile sensory signals.**

I. INTRODUCTION

Sensory and motor impairments, such as visual impairment in low vision individuals and motor impairments in individuals with multiple sclerosis, affect their effective interaction with the environment. For example, object manipulation abilities are strongly impaired in these situations [1], [2]. Given the important role of sensory modalities on interaction skills, there is a big effort to develop rehabilitation technologies, to evaluate the level of visual and tactile abilities quantitatively and improve rehabilitation protocols. Scientific evidence shows that the same environmental property may be processed by more than one sensory system [3], [4], [5]. The result of such integration is the perception of a more precise estimate than any individual one [6], [7]. Thus a multisensory visual and tactile rehabilitation therapy based on appropriate multisensory stimulation can improve functional interaction (e.g., improving object manipulation and exploration in visual and motor deficits). In this context, we propose a new robotic solution that can be used to evaluate the perceptual functionalities (unisensory and multisensory abilities) and create further rehabilitation training based on multisensory integration. Here we focused on rotational motion processing. Visual and tactile coordination of motion rotation is crucial during object manipulation, and interaction between visual and tactile modalities has been previously reported. For example, studies reported evidence of cross-modal interactions for motion perception: visual motion can influence the apparent speed of tactile motion [8], [9] as well as the speed and direction of audio motion [10], [11]. Similarly, cross-sensory facilitation between vision and touch has been reported for motion processing in humans [12]. Although some works have investigated the mechanisms associated with visuo-tactile motion integration, there are currently no solutions for multisensory motion rotation processing. To fill this gap in both the scientific and technological fields, we developed a new system, named RoMAT (Robot for Multisensory Analysis and Testing). The latter is a visual-

Fig. 1. Photograph of the RoMAT device, with its outer covers removed.

tactile robotic platform consisting of two rotating wheels with a customizable surface (see Fig.1). This system permits the presentation of multiple motion stimuli with independent directions of motion, thanks to four degrees of freedom (DOF) translation and rotation stimulations with high spatial and temporal resolution.

The RoMAT was conceived as an easily portable system, and it allows the employment of complex motion sensorial stimuli embedded in a compact structure. Indeed, the

[1]All authors are with the Fondazione Istituto Italiano di Tecnologia, Genova, 16163, Italy
[a]U-VIP Unit for Visually Impaired People
monica.gori@iit.it
[b]EDL Electronic Design Facility
[c]MWS Mechanical Design and Manufacturing Facility

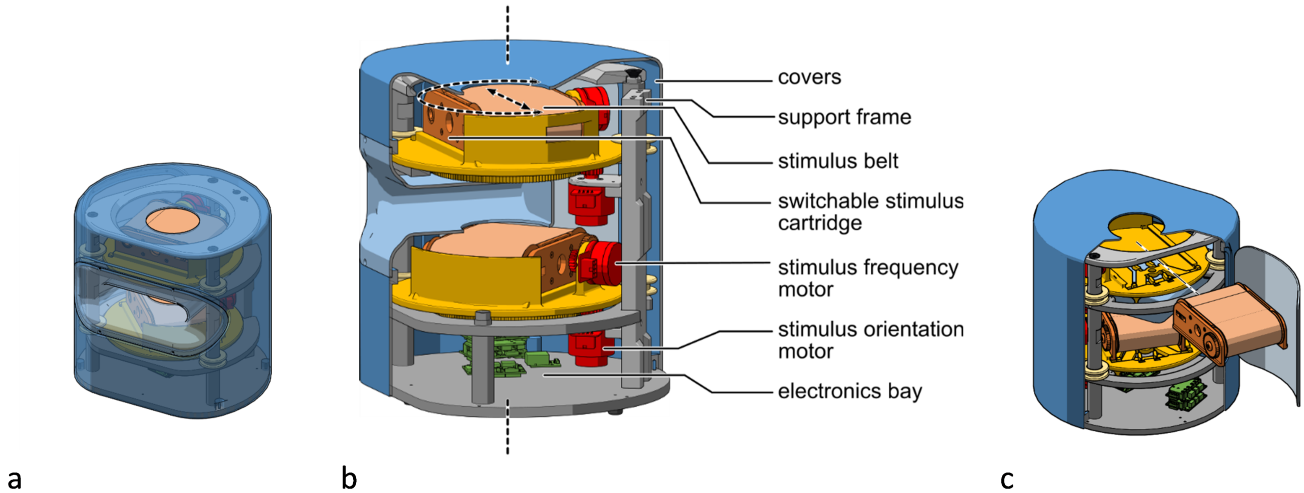

Fig. 2. CAD views of the RoMAT. The figure shows three CAD representations of the RoMAT device. View (a) shows an external view of the system with the covers in transparency. View (b) shows a cross setion of the device, highlighting its main parts and components. View (c) represents the quick-switch system for substituting the "cartridges" carrying the various stimulation patterns.

visual and tactile elements can be moved in complex bi-dimensional trajectories and can be personalized with desired textures. From a clinical perspective, the RoMAT would allow the clinician to investigate visuo-tactile and multi-sensory processing. Furthermore, it would allow to identify dysfunctionalities of theses components in individuals with visual and motor impairments on object exploration deficits (e.g., multiple sclerosis and low vision individuals), thus providing a convenient instrument for diagnostic and therapeutic purposes. It might also be used as a training device to facilitate object motion processing through the integration between vision and touch in these individuals. To investigate the effectiveness of the system, here we designed a rotation discrimination task and tested it in unisensory and multisensory conditions.

II. METHODS AND MATERIALS

A. Mechanical design

The design of the device originated from that of an earlier setup used in [12]. The Grooved Rings Device (GRD) used in this previous study allowed the control of the visuotactile stimulation in one direction. However, the direction of each stimulus needed to be set manually for each experiment. The first substantial upgrade described in this work is the addition of a second, actively controlled degree of freedom for both the visual and tactile stimuli. The design of RoMAT started with a set of quantitative specifications regarding the needed characteristics of the visuotactile stimuli. Besides providing the possibility to control the direction of the stimuli, the device needed to provide periodic stimulations with a spatial frequency ranging from 0.05[mm^{-1}] to 0.5[mm^{-1}], onto an area of at least 90[mm] by 90[mm]. The desired linear velocity range of the stimuli was 0.05[m/s] to 0.5[m/s]. Furthermore, the visuotactile stimulations needed to happen on two parallel planes closer than 50[mm]. Finally, RoMAT needed to allow for a deviation of the two stimuli directions up to 90°.

Besides these quantitative specifications, the design of the device also considered a set of more generic and qualitative specifications. The device needed to:

- be robust and durable to allow continuous and repeated experimentation without the need for maintenance;
- allow for quick switching of stimulation patterns for proving the maximum flexibility in the experimental conditions;
- be affordable and easy to replicate to make it accessible and remove all barriers for study replication;
- allow for changes to simplify future system upgrades; and
- be self-contained with no pinch points for increased user safety.

We considered several system architectures based on a previous device. The addition of the second degree of freedom implied that the GRD architecture was no longer suitable. We decided to substitute the grooved rings of the GRD with a flexible belt so that when moving the two stimulation planes closer together, we would not be constrained by the primary ring diameter. The belt would feature appropriate patterns to provide visual and tactile stimulations; the embodiement of this mechanism resembles that of a tapis-roulant. The mechanical design of the device is represented in detail in Fig.2

The stimuli used in this work were a series of ridges on the outer part of the belt having a uniform spacing of 12.75[mm] (hence a spatial frequency of ≈0.078[mm^{-1}]). We integrated the belt within a quick-release cartridge to allow fast changes of the shape and frequency of the pattern of the stimuli. From our preliminary tests, this design allows the experimenter to switch patterns in less than 20s.

The resulting device is a four DOF robot with two position-controlled joints and two velocity-controlled joints.

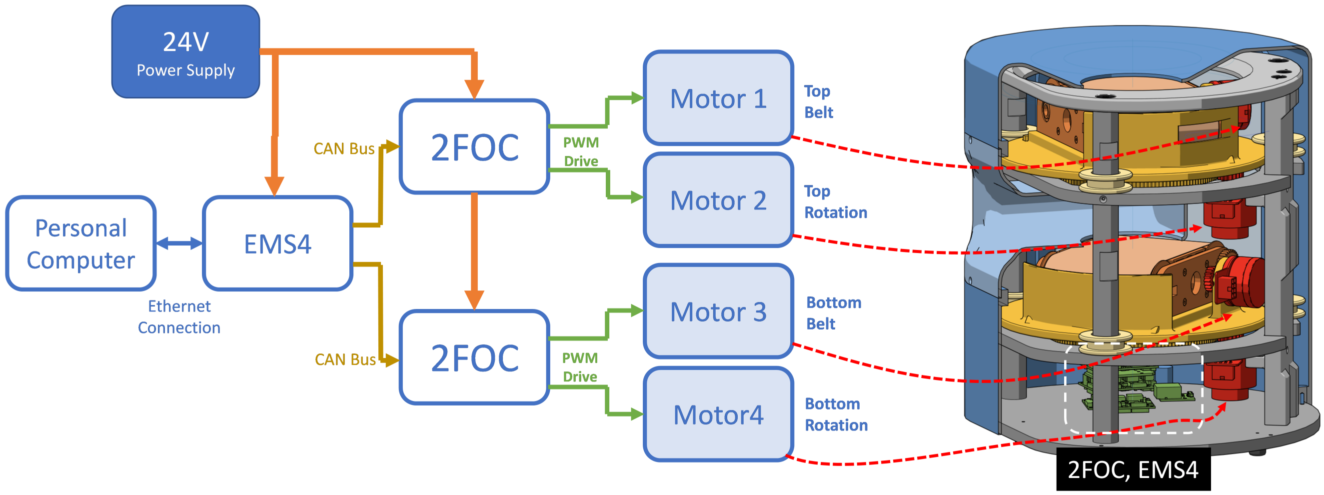

Fig. 3. Simplified block diagram of the electronic system used to control the four motors of the RoMAT.

We designed the device to enable its easy replication. We used commercial components wherever possible and designed all custom parts for additive manufacturing in plastics. In this way, all parts can be purchased from online suppliers providing on-demand 3D-printing and mechanical components. Also, the adoption of additive manufacturing allows the integration of multiple components, thus minimizing assembly operations. All the components were fabricated in PA12 by Selective Laser Sintering (SLS) on a ProX SLS 6100 machine by 3D Systems. Brush-Less DC (BLDC) motors actuate the four degrees of freedom, coupled to a geared transmission to reduce the motor velocity. A MaxonMotor EC45 Flat 70W BLDC motor drives each stimulus orientation DOF. The continuously rotating DOF are instead obtained with MaxonMotor EC45 Flat 50W BLDC motor. The BLDC motor velocities are reduced with spur gear transmissions. The stimulus orientation DOF has a 7:1 reduction ratio, while the stimulus frequency DOF has a 2:1 reduction ratio. We computed custom high-precision gear profiles with the MitCalc 2.80 software and integrated them directly into the custom-made parts of the device.

B. Electronic design

The device includes two motors for the top plate and tapis-roulant and two motors for the bottom plate and tapis roulant; all motors are blushless and can be controlled independently. The experimenter can choose to command the rotation of any DOF based on the desired experimental condition. To ease experiment execution, the complete system is designed to be interfaced to a Personal Computer (PC) using a standard Ethernet connection. The use of Ethernet compared to other physical buses such as Universal Serial Bus (USB) is preferable because the device can be located at a significant distance from the experimenter. Therefore, if needed, the experimenter can choose to run experimental sessions from the desired location withouth being constrained by the distance from the device.

A Python GUI program has been developed to control the system from a Linux-based laptop. The system is powered with an external 24V power supply. The electronic part is made up of an Ethernet Motor Supervisor (EMS4) board, which implements the physical Ethernet connection to the PC, and two 2-Field Oriented Control (2FOC) boards that are in charge of driving the motors implementing the Field Oriented Control algorithm, generating the Pulse Width Modulation (PWM) and running nested current and speed Proportional Derivative and Integrative (PID) controls. Each 2FOC board can drive two motors. Fig.3 shows a simplified block scheme for the control of the four motors of the RoMAT.

The EMS4 board is connected to the 2FOC boards using two dedicated Controller Area Network (CAN) bus interfaces; it implements Ethernet-CAN gateway functionality, to enable the PC to communicate directly with the 2FOC boards, and it can also run a position control PID and generate a minimum jerk trajectory on its own. To implement effective and robust control, each motor is equipped with both Hall-effect sensors and an incremental encoder that are connected to the 2FOC board (not shown here for the sake of brevity). In the current implementation, (that can be improved or changed based on the requirements of the experimenter), the 2FOC board runs current and speed control on all motors. For Motor 1 and Motor 3, that are responsible for the movement of the belt, the PC directly generates the required speed set-points. For the rotation motors Motor 2 and Motor 4, the EMS4 module sends speed set-points to the 2FOC board on the basis of the minimum jerk trajectory calculated from the desired final angular position and rotation speed requested by the PC.

C. Experimental protocol

To test the effectiveness of the RoMAT it has been used as a length discrimination task involving visual, tactile, or visual-tactile stimuli on four healthy individuals (i.e. no visual and motor deficits). Participants were naive to the study and recruited within IIT. The experimenter informed

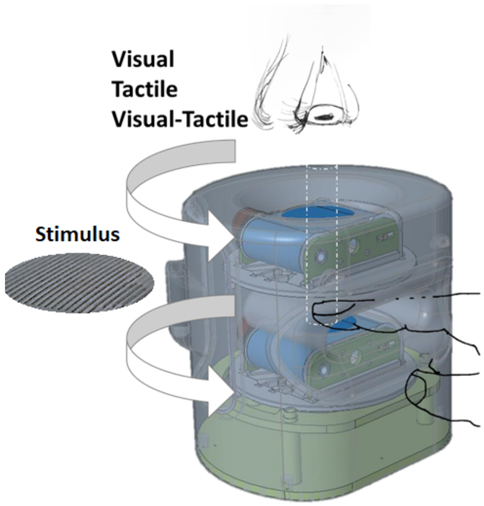

Fig. 4. Experimental procedure of the paradigm. Subject perceived two rotating stimuli and had to evaluate which of the two lasted longer.

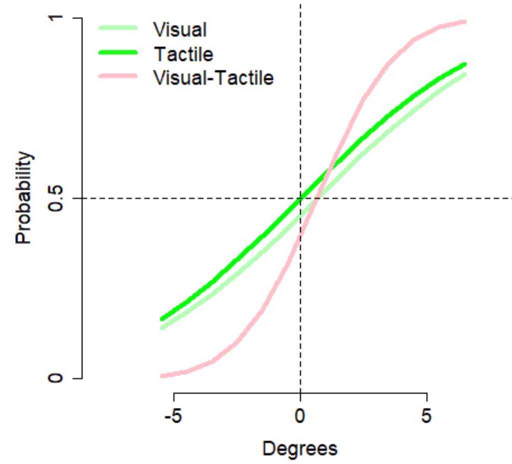

Fig. 5. Psychometric functions of one subject for the visual (in cyan), tactile (in green) and visual-tactile (in red), rotation discrimination tasks. The figure plots the proportion of trials where the first rotation was perceived as "longer" than the second as a function the rotation of the first stimulus normalized with respect to the 20°midline (i.e. -5 means that the fisrt rotation was of 15°and the second one of 25°). Data were fit with cumulative Gaussian error functions, whose mean (50% point) gives the "point of subjective equality" (PSE) spatial position for which the first stimulus, on average, appeared to be equal to the second stimulus, and the standard deviation (σ), or discrimination threshold.

the participants about the procedure. Two example trials were performed to explain the task before the experiment started. The stimuli used on the RoMAT were physical grids with a periodic pattern (Fig.4), driven by two independent computer-controlled motors. Stimuli were positioned on the top of the device and subjects observed the top plate (distance of 25 cm) and felt the second plate (concealed from view) with their index finger. The stimuli were spatially aligned to give the appearance of an everyday object (See Fig.4).

Unisensory (visual and tactile) and multisensory (visual-tactile) rotation precision was measured with a 2 Interval Forced Choice procedure, where subjects chose the longer perceived movement between a sequence of two rotations of the stimulus. The rotation movement started at 0°or at 40°. The movement was randomized between left and right: sometimes it started at 0°, and the ended at 40°, some other times it started at 40°and ended at 0°. The stimulus started from the first position (0°or 40°), moved until a second step and then stopped at the third position (40°or 0°). The second presentation was presented near threshold (with a constant stimuli procedure). The intermediate positions considered were: 15°; 18°; 20°; 22°; 25°. Each stimulus speed was maintained constant. One tactile (i.e., tactile rotation discrimination, only tactile stimulation without vision), visual (i.e. visual-tactile rotation discrimination, only visual discrimination without touch) and visual-tactile (i.e., visual-tactile rotation discrimination, both visual and tactile stimulations provided) stimuli were presented.

For each sensory condition (i.e. visual, tactile and visual-tactile conditions), subjects performed 24 trials, fitted with the psychometric function to extract the sensory threshold. The proportion of responses indicating the proportion of perceiving the first stimulus as longer in duration of motion was plotted as a function of the angle presented. Data were fit with a Cumulative Gaussian function (see Fig.5) by means of the Maximum Likelihood method to estimate both Point of Subjective Equality (PSE, given by the mean) and threshold (standard deviation). Data were fit with a raised cumulative Gaussian function and standard errors in the thresholds were computed with bootstrap simulation [13]. The space constant (σ) of the fit was taken as the estimate of a threshold indicating precision for the rotation direction discrimination task. All participants gave informed consent prior to testing. The study was approved by the ethics committee of the local health service (Comitato Etico, ASL3, Genova).

III. RESULTS AND DISCUSSION

A. *Experimental Results and discussion*

As mentioned above, participants performed three types of rotation discrimination tasks, one for each sensory modality investigated, and one involving the two modalities together. According to results, the RoMAT gives us the possibility to estimate unisensory and multisensory rotation thresholds. Fig.5 reports the psychometric functions of a typical participant for the visual (in cyan), tactile (in green), visual-tactile (in red) rotation discrimination tasks.

The proportion of trials where the stimulus was reported to rotate longer was plotted as a function of the rotation movement of the stimulus (relative to the midline of 20°). Considering the unisensory conditions first, the healthy participants reported (Fig.5) a psychometric function with low steepness for the tactile and visual conditions, suggesting a poor precision in performing the tactile and visual rotation task and revealing a need of stronger effort. On the other hand, the psychometric function for the multisensory condition is the steepest, revealing a strong effect of multisensory

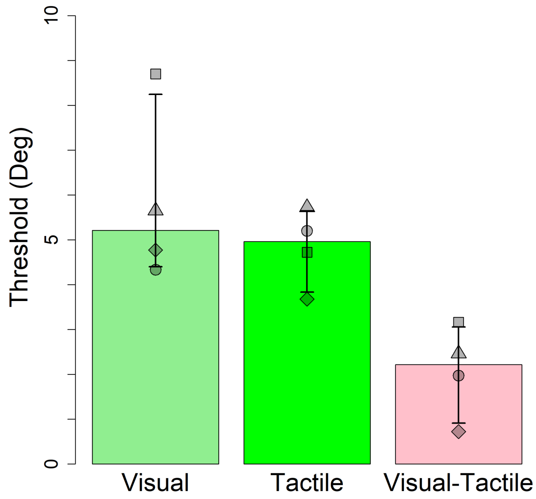

Fig. 6. Results (mean ± standard deviation) at the different rotation tasks for a group of four healthy individuals. Symbols represent individual data.

TABLE I

RESULTS OF THE T-TESTS COMPARING SPATIAL THRESHOLDS AMONG VISUAL-TACTILE (VT), TACTILE (T) AND VISUAL (V) ROTATION DISCRIMINATION TASKS. THE T STATISTIC (T), AND CORRESPONDING DEGREES OF FREEDOM (DF) AND P VALUE (P) ARE REPORTED FOR EACH COMPARISON

Task1	Task2	t	Df	p
VT	V	6.765	3	0.007
VT	T	5.573	3	0.01
V	T	1.322	3	0.28

integration on rotation discrimination precision when both sensory modalities were available. Indeed, in the multisensory context, the steepness of the psychometric function is higher than both the individual ones in the unisensory contexts.

Repeated measures one-way ANOVA run on the data, with condition as a within-subject factor with four levels (visual-tactile, visual and tactile), showed a significant difference across the unisensory and multisensory tasks ($F_{2,6} = 14.882$, $p = 0.005$). Individual rotation thresholds for all discrimination tasks are shown in Fig.6. Averaged data confirmed the results suggested by the individual psychometric functions. The mean spatial threshold are similar between the tactile and the visual discrimination task. Moreover, the multisensory rotation discrimination task is characterized by the lowest spatial threshold, suggesting strong multisensory integration under this condition. Although the sample size is limited and can be increased in the future and we can consider this a preliminary study, all these assumptions are confirmed by the post hoc two-tail t-test analysis (see Tab.I).

IV. CONCLUSIONS

We presented a novel device to investigate motion perceptual capabilities in dynamic environments, such as rotation of a moving target. The experimental validation of the system confirmed its effectiveness in improving motion sensitivity when multiple senses are available, as previously reported by other more simple systems. Furthermore, we implemented a novel paradigm, comparing rotation discrimination accuracy across visual and tactile sensory modalities. Motion rotation is based on perceiving complex dynamic spatiotemporal features of a stimulus to integrate two-dimensional vectors of motion. With the present study, we demonstrated that tactile and visual information could be used to discriminate motion rotation and that multisensory signals improve such ability. This finding may suggest that multisensory visual-tactile feedback could improve the motion perceptual capabilities of individuals with motor or visual disabilities by providing more robust information than with unimodal feedback. Several studies investigated how movement abilities change when sensory input is temporarily and/or partially unavailable, demonstrating multisensory inputs are crucial to perceive moving targets [14,15,16]. Overall, our work suggests that visual and tactile information could indeed be effective in rehabilitating movement capabilities in the presence of a visual or motor deficit. To conclude, these findings shed light on the role played by multisensory integration abilities in motion discrimination and, therefore, they highlight the importance of developing and testing motion integration processing and facilitation abilities in individuals with sensory and motor impairments. RoMAT can be an effective system to be used in this context in clinical and rehabilitation settings as a screening and rehabilitating sensory skills with activities based on multiple sensory stimulations.

ACKNOWLEDGMENTS

We thank Claudio Lorini of EDL, IIT for the electronic support. This work has been partially supported by the ERC MySpace project, PI Monica Gori, G.A: 948349

REFERENCES

[1] V. Krishnan, P. B. de Freitas, and S. Jaric, "Impaired object manipulation in mildly involved individuals with multiple sclerosis," Motor Control, vol. 12, no. 1, pp. 3-20, Jan 2008.
[2] G. Purpura, E. Febbrini Del Magro, R. Caputo, G. Cioni, and F. Tinelli, "Visuo-haptic transfer for object recognition in children with peripheral visual impairment," Vision Res, vol. 178, pp. 12-17, Jan 2021.
[3] B. E. Stein and T. R. Stanford, "Multisensory integration: current issues from the perspective of the single neuron," Nat Rev Neurosci, vol. 9, no. 4, pp. 255-66, Apr 2008.
[4] M. O. Ernst and H. H. Bülthoff, "Merging the senses into a robust percept," Trends in cognitive sciences, vol. 8, no. 4, pp. 162-169, 2004.
[5] M. S. Beauchamp, "See me, hear me, touch me: multisensory integration in lateral occipital-temporal cortex," Curr Opin Neurobiol, vol. 15, no. 2, pp. 145-53, Apr 2005.
[6] M. O. Ernst and M. S. Banks, "Humans integrate visual and haptic information in a statistically optimal fashion," Nature, vol. 415, no. 6870, pp. 429-33, Jan 24 2002.
[7] D. Alais and D. Burr, "The ventriloquist effect results from near-optimal bimodal integration," Curr Biol, vol. 14, no. 3, pp. 257-62, Feb 3 2004.
[8] S. J. Bensmaia, J. H. Killebrew, and J. C. Craig, "Influence of visual motion on tactile motion perception," J Neurophysiol, vol. 96, no. 3, pp. 1625-37, Sep 2006.
[9] J. C. Craig, "Visual motion interferes with tactile motion perception," Perception, vol. 35, no. 3, pp. 351-67, 2006.
[10] J. López-Moliner and S. Soto-Faraco, "Vision affects how fast we hear sounds move," Journal of Vision, vol. 7, no. 12, pp. 6-6, 2007.

[11] A. Mays and J. Schirillo, "Lights can reverse illusory directional hearing," Neuroscience letters, vol. 384, no. 3, pp. 336-338, 2005.
[12] M. Gori, G. Mazzilli, G. Sandini, and D. Burr, "Cross-sensory facilitation reveals neural interactions between visual and tactile motion in humans," Frontiers in psychology, vol. 2, p. 55, 2011.
[13] B. Efron and R. J. Tibshirani, An introduction to the bootstrap. CRC press, 1994.
[14] L. Shams and A. R. Seitz, "Benefits of multisensory learning," Trends in cognitive sciences, vol. 12, no. 11, pp. 411-417, 2008.
[15] S. Soto-Faraco, A. Kingstone, and C. Spence, "Multisensory contributions to the perception of motion," Neuropsychologia, vol. 41, no. 13, pp. 1847-1862, 2003.
[16] D. Senkowski, D. Saint-Amour, S. P. Kelly, and J. J. Foxe, "Multisensory processing of naturalistic objects in motion: a high-density electrical mapping and source estimation study," Neuroimage, vol. 36, no. 3, pp. 877-888, 2007.