Multisensory integration and its plasticity - How do innate and postnatal factors contribute to forming individual differences?

Kitada, Ryou
Sadato, Norihiro

(Citation)
Cortex,145:A1-A4

(Issue Date)
2021-12

(Resource Type)
journal article

(Version)
Accepted Manuscript

Special Issue Editorial

Multisensory integration and its plasticity – how do innate and postnatal factors contribute to forming individual differences?

Ryo Kitada[1, 2] and Norihiro Sadato[3]

1. School of Social Sciences, Nanyang Technological University, Singapore

2. Graduate School of Intercultural Studies, Kobe University, Japan

3. National Institute for Physiological Sciences, Japan

A topic of considerable interest in neuroscience is how different sensory modalities are integrated by the nervous system into a single, coherent perception (multisensory integration), and how internal and external environments influence multisensory perception and underlying mechanisms (plastic change). Since the discovery of multisensory integration principles in the cat's superior colliculus (Stein & Meredith, 1993), the field of multisensory research has been growing by incorporating psychophysical, neurophysiological, neuroimaging, and computational techniques. The number of research articles indexed by the keyword ”multisensory” has increased for the last decade (Stein et al., 2020).

Our sensation and perception are formed by the interaction of innate and postnatal factors. Because such interaction differs among individuals, our experience of multisensory perception would also diverge. For instance, congenital blindness can not only affect the sensitivity of the remaining senses but also changes audio-tactile integration (Champoux et al., 2010). Some individuals, who have strong cross-modal associations without sensory loss, can experience synesthesia (e.g., sound-to-color synesthesia). Based on findings from young, healthy, and typically developed individuals, there has been a growing trend to investigate multisensory perception in diverse physiological and pathological conditions. Then, what framework can explain multisensory perception irrespective of such conditions?

Moreover, the interplay of innate and postnatal factors can shape our cognition beyond sensation and perception. For instance, individuals with autism spectrum disorder (ASD) who have difficulty in social communication and interaction do not adhere to Weber's law, a central principle of sensory processing (Hadad & Schwartz, 2019). This atypical sensory processing in people with ASD was found in vision and haptics, indicating the link between multisensory perception and high-order cognition. This link can be applied to non-ASD individuals, assuming ASD as a variability rather than a pathology. Thus, one of the challenges in multisensory research is to understand how individual differences in multisensory perception are related to various aspects of cognition.

In this editorial, we introduce three main points learned from the special issue. The first point is the application of the Bayesian framework to multisensory perception in different physiological and pathological conditions. The Bayesian framework can describe reliability (likelihood) of multiple sensory representations, prior knowledge, causal inference, and decision-making strategies (Ernst & Banks, 2002; Körding et al., 2007; Wozny et al., 2010). For instance, Magnotti et al. (2020) employed this model to explain speech perception and the McGurk effect within the common computational framework (Magnotti et al., 2020, volume 133, page 371-383).

Two articles in the special issue employed the Bayesian framework to explain aging effects on multisensory integration. Jones & Noppeney (2021) outlined the impact of healthy aging on multisensory integration within the Bayesian framework (volume 138, page 1-23). They argued that sensory reliability, prior expectations, and decisional strategies contribute to age differences. Park et al. (2021) employed the Bayesian framework and attributed age-change in the ventriloquism effect to a decline in spatial hearing (volume 135, page 298-310).

Likewise, this special issue contained other findings which are consistent with the framework. For instance, Horváth et al. (2021) demonstrated that participants with more proprioceptive bias toward the direction of the rubber hand reported a stronger felt embodiment in the rubber hand illusion (volume 132, page 361-373). The same framework may explain cultural/linguistic effects on the development of audiovisual speech perception (Sekiyama et al., 2020, volume 140, page 145-156), long-term gaming effect on the Sound-Induced Flash Illusion (SIFI) (Di Luzio et al., 2021, volume 134, page 223-238), and the effect of hearing aids and age-related macular degeneration on the SIFI (Hirst et al., 2020, volume 133, page 161-176).

By contrast, neuroimaging studies on multisensory integration are not yet as strongly connected to this Bayesian framework. Three neuroimaging studies in this issue provided evidence for multisensory integration in the human brain (Porada et al., 2021, volume 139, page 198-210; Ronga et al., 2021, volume 144, page 133-150; Rosemann et al., 2020, volume 129, page 266-280). Two studies among them (Porada et al., 2021; Ronga et al., 2021) used supra-additive responses to sensory inputs, which were considered as neurophysiological evidence for multisensory integration (Calvert et al., 2000; Raij et al., 2000; Stein & Meredith, 1993). However, it is not clear how the supra-additive effect is related to a computational framework and linked to behavior (except for stimulus detection and localization). Alternatively, a previous study revealed that neurons in the dorsal medial superior temporal (MSTd) of non-human primates combined visual and vestibular inputs in a weighted linear fashion, consistent with the Bayesian framework (Fetsch et al., 2013). A few neuroimaging studies have employed Bayesian causal inference to demonstrate a hierarchy of multisensory processing in the human brain (Rohe & Noppeney, 2015, 2016). Thus, it is essential to adopt such a new approach and consider similarities and differences between conventional and new approaches.

The second key point was the link between atypical multisensory processing and cognitive processing. The special issue included three research articles on synesthesia (Ward et al., 2021 volume 139, 249-266; Ovalle-Fresa et al., 2021 volume 140, page 14-25; Lungu et al., 2021, volume 141, page 322-330). These studies demonstrated behavioral and neural activity patterns that are unique to synesthetes. For instance, Ovalle-Fresa et al. (2021) showed that grapheme-color synesthetes and color experts had better visual perceptual ability and memory than non-synesthetic control subjects. Though these studies involved attributes of objects within vision, this supports the interplay between sensory and cognitive processing.

Ainsworth et al. (2021) provided more direct evidence for the link between sensory and cognition processing in the context of multisensory integration (volume 134, page 195-206). In this study, autistic participants showed reduced audiovisual facilitation of response time compared to neurotypical subjects. This finding is consistent with the framework that atypical sensory processing is associated with higher-level core aspects of ASD. This finding is supported by a previous study in which congenital blindness delayed the development of social skills - congenitally blind children were misdiagnosed as ASD (Hobson & Lee, 2010). Thus, it is worth investigating how atypical sensory processing shapes differences in social cognition.

The third point is the impact of comorbid impairments on the research of sensory loss. More specifically, Moïn-Darbari et al. (2021) maintained that, though a large proportion of deaf people in studies had significant vestibular damage, this factor has been overlooked in hearing loss studies (volume 138, page 311-317). This is a critical caution to understand further the impact of sensory loss on neural mechanisms for sensory processing.

The special issue also included research articles on the effect of congenital sensory deprivation (Bednaya et al., 2021, volume 142, page 138-153; Kanjlia et al., 2020, volume 142, page 342-356). Findings in these studies are largely in accord with the view that while sensory loss affects early sensory cortices, higher-order cortical regions still retain some of their functions (e.g., Ricciardi & Pietrini, 2011; Kitada, 2016). For instance, Kanjlia et al. (2021) found that number representation in the intraparietal sulcus was present in both congenitally blind and sighted individuals. Togoli et al. (2021) conducted a psychophysical study to show tactile numerosity representation is coded in allocentric coordinates rather than egocentric representation (volume 134, page 43-51). Thus, it is interesting in the future to investigate how activity in the network involving the IPS accounts for allocentric-based numeriocity representation.

Collectively, studies in this special issue updated our current understanding of multisensory perception. The Bayesian approach will continue to be a promising framework to explain various aspects of multisensory integration. While a few studies indicated the link between perception and other parts of cognition, more evidence is necessary to understand the underlying mechanisms. For instance, the core abnormality of ASD is related to perceptual aberrations due to a disbalance between the reliablity of prediction errors and the reliability of predictions (Haker et al., 2016). Thus, further explorations are necessary by combining psychophysics, neurophysiology, and computational perspectives.

Acknowledgments

This work was supported by an NAP start-up grant from Nanyang Technological University and MEXT/JSPS KAKENHI (Fund for the Promotion of Joint International Research, 20K23372), Japan to RK.

References

Ainsworth, K., Ostrolenk, A., Irion, C., & Bertone, A. (2021). Reduced multisensory facilitation exists at different periods of development in autism. *Cortex*, 134, 195–206. https://doi.org/10.1016/j.cortex.2020.09.031

Bednaya, E., Pavani, F., Ricciardi, E., Pietrini, P., & Bottari, D. (2021). Oscillatory signatures of Repetition Suppression and Novelty Detection reveal altered induced visual responses in early deafness. *Cortex*, 142, 138–153. https://doi.org/10.1016/j.cortex.2021.05.017

Calvert, G.A., Campbell, R., Brammer, M.J., (2000). Evidence from functional magnetic resonance imaging of crossmodal binding in the human heteromodal cortex. *Current Biology,* 10, 649–657. https://doi.org/10.1016/S0960-9822(00)00513-3

Champoux, F., Collignon, O., Bacon, B. A., Lepore, F., Zatorre, R. J., & Théoret, H. (2011). Early- and late-onset blindness both curb audiotactile integration on the parchment-skin illusion. *Psychological Science*, 22, 19–25. https://doi.org/10.1177/0956797610391099

Di Luzio, P., Borgomaneri, S., Sanchioni, S., Tessari, A., & Romei, V. (2021). Exposure to first-person shooter videogames is associated with multisensory temporal precision and migraine incidence. *Cortex*, 134, 223–238. https://doi.org/10.1016/j.cortex.2020.10.009

Ernst, M. O., & Banks, M. S. (2002). Humans integrate visual and haptic information in a statistically optimal fashion. *Nature*, 415, 429–433. https://doi.org/10.1038/415429a

Fetsch, C. R., DeAngelis, G. C., & Angelaki, D. E. (2013). Bridging the gap between theories of sensory cue integration and the physiology of multisensory neurons. *Nature Reviews Neuroscience*, 14(6), 429–442. https://doi.org/10.1038/nrn3503

Hadad, B. S., & Schwartz, S. (2019). Perception in autism does not adhere to Weber's law. *eLife*, 8, e42223. https://doi:10.7554/eLife.42223

Haker, H., Schneebeli, M., & Stephan, K. E. (2016). Can Bayesian Theories of Autism Spectrum Disorder Help Improve Clinical Practice?. *Frontiers in psychiatry*, 7, 107. https://doi.org/10.3389/fpsyt.2016.00107

Hirst, R. J., Setti, A., De Looze, C., Akuffo, K. O., Peto, T., Kenny, R. A., & Newell, F. N. (2020). The effect of eye disease, cataract surgery and hearing aid use on multisensory integration in ageing. *Cortex*, 133, 161–176. https://doi.org/10.1016/j.cortex.2020.08.030

Hobson, R. P., & Lee, A. (2010). Reversible autism among congenitally blind children? A controlled follow-up study. *Journal of Child Psychology and Psychiatry, and Allied Disciplines*, 51, 1235–1241. https://doi.org/10.1111/j.1469-7610.2010.02274.x

Horváth, Á., Ferentzi, E., Bogdány, T., Szolcsányi, T., Witthöft, M., & Köteles, F. (2020). Proprioception but not cardiac interoception is related to the rubber hand illusion. *Cortex*, 132, 361–373. https://doi.org/10.1016/j.cortex.2020.08.026

Jones, S. A., & Noppeney, U. (2021). Ageing and multisensory integration: A review of the evidence, and a computational perspective. *Cortex,* 138, 1–23. https://doi.org/10.1016/j.cortex.2021.02.001

Kanjlia, S., Feigenson, L., & Bedny, M. (2021). Neural basis of approximate number in congenital blindness. *Cortex*, 142, 342–356. https://doi.org/10.1016/j.cortex.2021.06.004

Kitada, R. (2016), The Brain Network for Haptic Object Recognition. In H. Kajimoto, S. Saga, &

M. Konyo (Eds.), *Pervasive Haptics* (pp. 21-38). Springer, Tokyo. https://doi.org/10.1007/978-4-431-55772-2_2

Körding, K.P., Beierholm, U., Ma, W.J., Quartz, S., Tenenbaum, J.B., & Shams, L. (2007). Causal Inference in Multisensory Perception. *PLoS ONE,* 2, e943. https://doi.org/10.1371/journal.pone.0000943

Lungu, L., Rothen, N., & Terhune, D. B. (2021). The time course of synaesthetic colour perception. *Cortex*, 141, 322–330. https://doi.org/10.1016/j.cortex.2021.04.018

Magnotti, J. F., Dzeda, K. B., Wegner-Clemens, K., Rennig, J., & Beauchamp, M. S. (2020). Weak observer–level correlation and strong stimulus-level correlation between the McGurk effect and audiovisual speech-in-noise: A causal inference explanation. *Cortex*, 133, 371–383. https://doi.org/10.1016/j.cortex.2020.10.002

Moïn-Darbari, K., Lafontaine, L., Maheu, M., Bacon, B. A., & Champoux, F. (2021). Vestibular status: A missing factor in our understanding of brain reorganization in deaf individuals. *Cortex*, 138, 311–317. https://doi.org/10.1016/j.cortex.2021.02.012

Ovalle-Fresa, R., Ankner, S., & Rothen, N. (2021). Enhanced perception and memory: Insights from synesthesia and expertise. *Cortex*, 140, 14–25. https://doi.org/10.1016/j.cortex.2021.01.024

Park, H., Nannt, J., & Kayser, C. (2021). Sensory- and memory-related drivers for altered ventriloquism effects and aftereffects in older adults. *Cortex*, 135, 298–310. https://doi.org/10.1016/j.cortex.2020.12.001

Porada, D. K., Regenbogen, C., Freiherr, J., Seubert, J., & Lundström, J. N. (2021). Trimodal processing of complex stimuli in inferior parietal cortex is modality-independent. *Cortex*, 139, 198–210. https://doi.org/10.1016/j.cortex.2021.03.008

Raij, T., Uutela, K., Hari, R., (2000). Audiovisual integration of letters in the human brain. *Neuron,* 28, 617–625. https://doi.org/10.1016/S0896-6273(00)00138-0

Ricciardi, E., & Pietrini, P. (2011). New light from the dark: What blindness can teach us about brain function. *Current Opinion in Neurology*, 24, 357–363. https://doi.org/10.1097/WCO.0b013e328348bdbf

Rohe, T., & Noppeney, U. (2015). Cortical hierarchies perform Bayesian causal inference in multisensory perception. *PLoS Biology*, 13, e1002073. https://doi.org/10.1371/journal.pbio.1002073

Rohe, T., & Noppeney, U. (2016). Distinct Computational Principles Govern Multisensory Integration in Primary Sensory and Association Cortices. *Current Biology*, 26, 509–514. https://doi.org/10.1016/j.cub.2015.12.056

Ronga, I., Galigani, M., Bruno, V., Castellani, N., Rossi Sebastiano, A., Valentini, E., Fossataro, C., Neppi-Modona, M., & Garbarini, F. (2021). Seeming confines: Electrophysiological evidence of peripersonal space remapping following tool-use in humans. *Cortex*, 144, 133–150. https://doi.org/10.1016/j.cortex.2021.08.004

Rosemann, S., Smith, D., Dewenter, M., & Thiel, C. M. (2020). Age-related hearing loss influences functional connectivity of auditory cortex for the McGurk illusion. Cortex, 129, 266–280. https://doi.org/10.1016/j.cortex.2020.04.022

Sekiyama, K., Hisanaga, S., & Mugitani, R. (2021). Selective attention to the mouth of a talker in Japanese-learning infants and toddlers: Its relationship with vocabulary and compensation for noise. *Cortex*, 140, 145–156. https://doi.org/10.1016/j.cortex.2021.03.023

Stein, B.E., & Meredith, M.A. (1993). *The merging of the senses.* The MIT Press.

Stein, B. E., Stanford, T. R., & Rowland, B. A. (2020). Multisensory Integration and the Society for Neuroscience: Then and Now. *The Journal of Neuroscience*, 40, 3–11. https://doi.org/10.1523/JNEUROSCI.0737-19.2019

Togoli, I., Marlair, C., Collignon, O., Arrighi, R., & Crollen, V. (2021). Tactile numerosity is coded in external space. *Cortex*, 134, 43–51. https://doi.org/10.1016/j.cortex.2020.10.008

Ward, J., Baykova, R., Dyson, B., Chew, J., Schreiter, M. L., Beste, C., & Sherman, M. (2021). A distinct electrophysiological signature for synaesthesia that is independent of individual differences in sensory sensitivity. *Cortex*, 139, 249–266. https://doi.org/10.1016/j.cortex.2021.02.031

Wozny, D. R., Beierholm, U. R., & Shams, L. (2010). Probability matching as a computational strategy used in perception. *PLoS computational biology*, 6(8), e1000871. https://doi.org/10.1371/journal.pcbi.1000871