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MULTISENSORY RESEARCH

Viewpoints

Viewpoint on Multisensory Integration in Psychiatric Disorders

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Abstract

This article presents a compiled interview with three researchers in the field of multisensory integration, with an emphasis on how multisensory integration may go awry in psychiatric and neurodevelopmental conditions. Through structured dialogue, the authors reflect on the origins of the field, the development of key empirical and computational frameworks, and the growing relevance of multisensory science for understanding autism, schizophrenia, dyslexia, and related conditions. The discussion highlights the shift from descriptive accounts of multisensory phenomena toward normative models, including maximum likelihood estimation, causal inference, and correlation detection, as well as the need to link these computations to neural circuits and clinical heterogeneity. The authors consider ongoing challenges in the field, including inconsistent findings across clinical studies, limited statistical power, difficulties in defining and measuring multisensory function, and the need for larger, better-characterized cohorts. They also discuss emerging directions, including naturalistic paradigms, adaptive coding, open and team science, precision psychiatry, and the application of artificial intelligence to complex multimodal datasets. The interview concludes by emphasizing the promise of multisensory integration as a framework for understanding perception, cognition, and belief updating in health and disease.

Keywords

autism, schizophrenia, causal inference, dyslexia, electroencephalography, maximum likelihood estimation, normative models

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1. Interview

When did you first become involved in multisensory research, and what has motivated you to continue with it?

Mark T. Wallace: As a graduate student, I worked in a vision laboratory. My epiphany came when doing another in a series of late-night experiments. I realized that even if we were to understand everything about the visual system, we would still not understand perception, which is ultimately a multisensory construct. At the same time, Barry Stein and Alex Meredith were publishing their seminal papers. I reached out to Barry, and that began my multisensory journey.

Sophie Molholm: I became involved quite early on. Before 2000, there were very few human brain-imaging studies on multisensory integration, and the prevailing model held that integration occurred late, within higher-order convergence zones. But emerging anatomical work from Cathy Rockland, Arnaud Falchier, and others using retrograde tracers revealed monosynaptic connections between visual and auditory cortices, lending plausibility to the idea that multisensory interactions might occur earlier, even within sensory cortices themselves. My PhD thesis project on audiovisual integration, using scalp electrophysiology, supported this idea (Molholm *et al.*, 2002). My mentor was John Foxe and we were at the Nathan Kline Institute in Orangeburg, New York, where Charlie Schroeder also had his lab. It was truly a hotbed of multisensory research and we had a great time. I have remained engaged because much remains to be discovered. The interactions among the sensory systems are far from fully understood, and the ways in which they develop, change with aging, and diverge in psychiatric conditions are central to understanding human perception and cognition in health and disease.

Jean-Paul Noel: As a young student I was initially drawn to what some call the ‘hardest problem’ of them all: how can the 1.5 kilograms of meat in our skulls give rise to conscious experience? I began by approaching this question from a bottom-up perspective, aiming to identify the minimal components required for a sense of selfhood. This led me to the study of bodily self-consciousness, a field strongly rooted in the study of multisensory integration. For example, we perceive ourselves as located within our bodies because we see and feel touch in a spatially and temporally congruent way. To explore these foundational questions, I began my graduate studies in 2014, in the lab of Dr Mark Wallace, who is one of the pioneers of multisensory integration and a continued mentor to this day.

Which individuals have inspired you or had a significant impact on your research?

Jean-Paul: There are many I could mention. Olaf Blanke is a visionary unafraid to push the boundaries of current knowledge. Andrea Serino and

Mark Wallace have been exceptional mentors —- true guides in teaching me how to do science. I often came to them with data that contradicted our initial hypotheses, and their response was always the same: "This is even better!" That, to me, is science at its core: progress happens when data challenges our beliefs. Dora Angelaki, Greg DeAngelis, Marc Ernst, Martin Banks, and Ladan Shams helped move the field toward more quantitative, computational, and principled approaches. I deeply admire Uta Noppeney and Cesare Parise for their consistently outstanding work. Max Di Luca, Majed Samad, and Edoardo Balzani gave me the confidence to deepen my computational skills, profoundly shaping my research program today. These are just a few of the people who have and continue to inspire me: I could probably go on for pages.

Sophie: I am extremely fortunate to have crossed paths with so many intelligent, interesting, and genuinely fun people — both within science and outside it — who have inspired me and shaped my path as a researcher. John Foxe had a significant impact on my scientific development and trajectory. Not only did he introduce me to the multisensory sciences, but he also encouraged me to extend my work to clinical populations. Some 25 years later we are still collaborating in these areas. John Antrobus, a professor at the City College of New York, was the one who first introduced me to cognitive science and encouraged me to pursue graduate studies. My current and former students, postdocs, and research staff, and indeed a broad interdisciplinary network of collaborators over the years, have contributed greatly to my thinking and work, and I am grateful.

Mark: For me it was Barry Stein — the father of our field, who provided me with the opportunity to work with him, and who has taught me an enormous amount about success in science and academia. Ed Gruberg, my graduate mentor, who cultivated in me a thirst for science and who was a fabulous teacher. Alex Meredith, who took me under his wing and taught me mammalian neurophysiology. Randy Blakely, who showed me here at Vanderbilt how to run a large and successful lab, while keeping exacting standards.

What do you consider to be the most influential findings or model developments in your field over the past years or decades?

Mark: Historically I would have to begin with the original pair of *Science* papers of Meredith and Stein (1983, 1985), which gave birth to a new field. More recently, I would say Ernst and Banks (2002), for illustrating how multisensory operations can be formalized in the context of a normative model, and Lakatos *et al.* (2007), for showing how neuronal oscillations can shape multisensory processes. Of late, I have been struck by how pervasive alterations in multisensory integration are in neuropsychiatric and neurodevelopmental conditions, suggesting that they may contribute mechanistically, and may be useful in shaping future interventions. Multisensory areas and computations may be a convergence hub from sensation to cognition, and thus a critical nexus for understanding neurotypical and atypical brain function.

Jean-Paul: I believe that as a field, we want to understand domain-general, canonical computations. I think multisensory integration is a prime example of the broader computation of causal inference: how do we attribute signals to their underlying latent causes. In this context, we have to mention Ernst and Banks (2002), as well as Alais and Burr (2004; i.e., maximum likelihood estimation). Then we have to mention Kording and colleagues (2007; i.e., causal inference). And currently, we have to mention the work by Tim Rohe and Uta Noppeney. From the perspective of multisensory in psychiatry disorders we have to mention Foxe, Molholm, Wallace, Cascio, and Foss-Feigh, for really pioneering this field, and Pellicano, Burr, and Series, among others, for making it more principled. Moving forward, I think we need to translate these models into putative circuit models, and tackle these problems with millisecond and cellular resolution, in animal models allowing for more mechanistic understandings. I also think we need to move from discrete worlds, for example, a single auditory and visual event that may be synchronous or asynchronous to a continuous world where synchrony is not king, but correlation. Here we must talk about the work from Parise (2016). The work on multisensory correlation detection in psychiatry is still nascent. I also think somewhat underappreciated is the work by Ohshiro and colleagues (2011, 2017) which really brought two multisensory fields together: the original 'principles' of multisensory integration and the normative maximum likelihood perspective.

Sophie I agree with you, we are entering an exciting time in this field. We have gone from descriptions of multisensory phenomena to models that begin to explain them, and we are now beginning to understand underlying neural and computational mechanisms. Barry Stein and Alex Meredith's early work on multisensory integration (MSI) in the cat superior colliculus has been hugely influential, establishing foundational principles — such as spatial and temporal congruency — that continue to guide the field (Stein and Meredith, 1993). A major conceptual shift came from recognizing how extensively MSI operates across the brain. This has moved us away from models that treat the senses as largely independent channels and toward a view of perception as inherently interactive, with continuous cross-talk across sensory systems. Equally important is the body of research demonstrating the powerful role of early experience in shaping MSI. We now understand that through experience the immature brain learns how to combine and integrate multisensory cues in ways that enhance performance and support adaptive behavior — and that this learning unfolds over a relatively extended period of childhood. (e.g., Beker *et al.*, 2018; Ross *et al.*, 2011; Tonelli *et al.*, 2026).

How have these findings and models changed current research, and what are content and methodological trends in your field of research?

Mark: Ernst and Banks (2002) presaged the enormous growth in work attempting to model multisensory processes, models that are now being applied to better understand multisensory changes in neurodevelopmental and neuropsychiatric conditions. Lakatos and Schroeder became foundational for studies examining multisensory interactions in regions considered traditionally unisensory, but more importantly highlighted a very different mechanistic aspect of multisensory function, bringing a lens to the key role that neuronal oscillations play.

Jean-Paul: To me, the recent findings and models really show that MSI is a particular form of the broader computation of building generative models. It is also a very productive example, as the 'input nodes' (e.g., retina and cochlea) are independent. A clear example is autism, where I think some of us are starting to think that the difficulty is less so with sensory periphery or mechanisms of MSI *per se*, and more so with the process of inferring what is the causal structure that generated the observed sensory signals (e.g., Noel *et al.*, 2018; 2022; Noel and Angelaki, 2023). In terms of content and methodological trends, we have to do larger-scale studies, measure not only behavioral and neural responses, but characterize sensory histories, the environment, sensory periphery, etc. I think a productive approach — in particular in psychiatric conditions — may be to not measure steady states so much, but how networks adapt to changes in mean/variance/context of one's environment. A field some call 'adaptive coding'.

Sophie: Computational modeling is now a crucial aspect of the field. A key question moving forward is how to examine multisensory processes in more naturalistic settings. We have learned a great deal from studies using simplified stimuli, but how does MSI work in the complex, dynamic sensory environments we encounter every day. There is also increasing interest in understanding inter-individual differences in multisensory function and how these relate to broader phenotypic characteristics, including those related to clinical conditions.

What are the main controversies in your field of research?

Mark: Right now I would highlight, not necessarily a controversy, but rather the confusing state-of-the-field in regard to multisensory contributions to neuropsychiatric and neurodevelopmental conditions. The good news is that there's a great deal of interest in the topic. The bad news is that without systematic approaches the field remains mired in a host of conflicting findings. My hope is that this changes over the next three to five years.

Sophie: There are many open questions about the nature of multisensory processing in clinical populations. Are alterations in MSI a core feature of certain conditions, or are they secondary to other sensory or cognitive differences? How do we best characterize and measure multisensory function in these populations? What are the clinical implications of altered multisensory processing? These are critical questions that we are beginning to address.

Jean-Paul: I think there is some controversy surrounding how MSI is defined and measured, and which computational processes underlie it. There is also ongoing debate about the extent to which multisensory processing is context- or domain-specific *versus* context-agnostic and domain-general, and about whether mechanisms identified in controlled laboratory settings generalize to real-world situations. More broadly, there is growing recognition of the heterogeneity within many clinical populations (e.g., autism, schizophrenia), which has sparked debate over whether such populations should be treated as cohorts or as individuals. Precision psychiatry approaches offer great promise, while introducing their own set of challenges. Overall, I am not sure I would use the word 'controversy' but just a nascent literature that is full of conflicting results. The only way forward is larger studies, larger teams, better statistical power, pre-registration, etc.

Which finding(s) from the literature in your field would you like to see replicated?

Jean-Paul: More than a single finding, I would love to challenge our field to come together in adopting new team science approaches to science. We forget that neuroscience and the study of MSI are relatively young fields. We can learn a lot from more mature sciences, such as physics. Most of experimental physics today is done in two or three places, like CERN. Experts agree on which is the theoretically most important question we can answer today, or within the next five to 10 years. Then massive resources are poured into this endeavor. Experiments are replicated 10 times over before being considered true. We are seeing the advent of this approach in neuroscience, with efforts such as the Allen Institute, the International Brain Lab, or the Simons Collaboration for Ecological Neuroscience. I have been fortunate to be part of some of these collaborations. How fun and incredibly productive would it be to work toward this in our field?

Sophie: I think that much of the work on multisensory processing in clinical populations needs to be replicated with larger well-characterized samples. We also need more work examining the test–retest reliability of multisensory measures, which will be critical if we want to use these measures as biomarkers or outcome measures in clinical trials.

Mark: That is true, Sophie! I indeed would love to see much of my own work replicated. We design experiments that we think are best structured to address our hypotheses of interest. With that said, there are probably smarter people with better methods who can test these same hypotheses and I would love to see that. Truth is truth.

What are your thoughts on open-science practices in your field, and how have you implemented them in your research?

Sophie: Open-science practices are an extremely important evolution in the field for many reasons including increased transparency, better science, and simple economics. By sharing code for study implementation and data analysis, methods can be more fully evaluated, and more precisely replicated; making data accessible allows more scientists to work with the data, may lead to important discoveries, and can facilitate pooling of data across studies and laboratories; and sharing data makes research a better investment for society and for participants. In my lab we share code for data analysis and sometimes for paradigms/stimuli in our publications, and we have begun to share full datasets. These practices are becoming ever easier with agreed-upon standards and free tools and platforms for sharing. I think the field is moving in the right direction with open-science practices and that these will become commonly implemented, and in many cases required, over the next few years. To the extent there is resistance, it is probably often because open science takes resources of which none of us ever have enough. But over time we will learn to build this into planning of time and budgets so that it becomes a standard operating procedure.

Jean-Paul: I am a strong advocate for open and team science. I have over 20 projects publicly available on the Open Science Framework (OSF), and in my post-doctoral work I recorded from over 100k single neurons, each of which is available in open repositories online. In my lab, as soon as we record data from mice and this data are placed on our internal servers, they are also released within the Open Neuroscience Environment (ONE), a framework I helped develop within the context of the International Brain Lab.

Mark: I'm a big believer in open science. Our MELD (Multisensory Environments to study Longitudinal Development) consortium is predicated on open science, where we will make both our data and our paradigms freely available. I think such transparency is critical for us to be able to do our best science.

What progress or breakthroughs do you expect to see in the next 5–15 years? For example, what impact could the implementation of AI have on your field?

Jean-Paul: The field of MSI in psychiatry has been dominated by autism spectrum disorder and to a lesser extent schizophrenia. The results have been conflicting. I think in the next five years we will see two major developments. First, a more diversified approach and deeper consideration of other conditions, such as ADHD, OCD, dyslexia, and also the advent of the field of multisensory computational neurodegeneration, for example in Parkinson. I also think we should see a stronger focus on typical and atypical aging and MSI. Second, I think that autism spectrum disorder and schizophrenia will remain dominant, but we will see larger-scale studies. Not only in terms of sample sizes, but their clinical assessment, the number of methods used, experiments conducted, number of models pitted against each other. In the next 10–15 years, I also hope we will start understanding the neural mechanisms — from a single-cell perspective — supporting causal inference and how this computation goes awry in different disease states. I also hope this understanding will not only leverage insights from AI but actually drive its development. Perception is an active process wherein we invert hypothesized generative models, akin to large language models today. We have the unique opportunity to inform the development of more energetically efficient and more brain-like AI. This will not only catalyze next-generation AI but will also protect our environment against climate change. As neuroscientists, I think it's less interesting to ask how will AI impact our work, and more interesting to ask, how can our work impact AI?

Mark: I think we are going to see increasing evidence for the benefits of psychedelic compounds in the treatment of neuropsychiatric and neurodevelopmental conditions. Their effects on brain plasticity are becoming increasingly well established, and I think they will become major therapeutic tools. There is no doubt that AI will also be a major driver of change, particularly in the multisensory arena, where we will have an increasing ability to do experiments under more naturalistic conditions, and to analyze complex multimodal datasets that merge perceptual and neural data.

Sophie: Sooner than later many of us will be wearing sensors recording our bodily signals, like brain activity, pupillometry, heart rate, movement, and force, along with sensors measuring the signals coming into our nervous system such as sound, light, and touch. AI will be applied to sort through these temporally synchronized signals to get data-driven insights into how we shift attention, respond, and integrate or segregate multisensory inputs. This could lead to a major advance in understanding of sensory perception and MSI.

What advice would you give to a young scientist in the field specializing in MSI and how would you encourage them to pursue this field?

Sophie: Have fun and enjoy the journey! Find an area of the field to focus on and let your interests as well as the expertise and tools available to you guide you. Your interests and focus will likely evolve over time, but gaining deep domain expertise in some aspect of MSI will serve you well no matter where your career leads. Seek out supplementary training in the methods you'll need to advance your work, whether through a postdoc or the next postdoc, coursework and workshops, or collaborations.

Mark: The field is young! There are so many opportunities. I'm a big believer in building a large experimental toolbox early in your career. In this way, you can do experiments that span across scales of analysis. I was very lucky to have done neurophysiology early in my career. Even today, when I do many more human-oriented experiments, that training provides me with a unique lens in both the design and analysis of new experiments.

Jean-Paul: I would encourage young scientists in the field to be courageous in the methods they use. Pick a question and tackle it from as many different levels of description as you can. As a research assistant, graduate student, post-doc, join labs using different methods: human behavior, cellular or molecular techniques in rodents, physiology in primates, computational techniques, and so on. We learn most when we are slightly uncomfortable and I think our field will be stronger if we have young scientists trained in a variety of methods.

Is there anything else about your field of study that you would like to share with readers that hasn't been covered in previous questions?

Jean-Paul: I want to thank the field for being such an outstanding environment for young researchers. It's easy to get bogged down by day-to-day challenges. But I think we should all remember how important our work is, and what a privilege it is for us to be able to follow our curiosities each and every day. Perhaps today more than ever before. In a sense, the study of MSI — and how it goes awry in disease states — is the study of how we weigh different sources of evidence in updating our beliefs. Today we live in a world where beliefs seem to be more entrenched than ever before. Let's take a second to really dream of the impact our work could have.

Mark: For the young scientist, my advice is read! I see an increasing tendency to gloss over the prior literature, what is a huge mistake. This work, if you take the time to read it, is the foundation upon which your science should be based.

Dear Sophie, Jean-Paul, Mark, thank you for the interview!

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