Adaptive behaviour in our dynamic, multisensory real-world

Prof. Uta Noppeney, DCN/DCCN/Biophysics

Research in our Lab investigates how the brain enables us to perceive, understand and interact effectively with the multisensory world around us. When crossing a busy road our senses are bombarded with myriads of diverse signals: a sparkling bike passing by, the looming noise of a truck, the smell of traffic fumes. The effortless ease with which we merge these signals into a seamless percept masks the complexity of the computations and neural mechanisms involved. Multisensory integration raises some of the most fundamental questions for neural processing, notably decision-making, perceptual inference, learning and probabilistic/statistical computations. To define the underlying computations and neural mechanisms in the healthy and diseased human brain our lab combines behavioural, computational modelling (Bayesian, neural network) and neuroimaging (fMRI, MEG, EEG). For more information see attached feature article about our lab's research (before we moved to Donders Institute).

We are looking for enthusiastic MSc/BSc students with background / interests in

1. Experimental work: Psychophysics, fMRI, EEG, MEG

2. Computational modelling (e.g. Bayesian inference, neural network)

MSc projects will be defined together with the student to match interests, training background (e.g. computational, neuroimaging, psychophysics) and skills.

Potential questions:

- Solving the binding problem in the real world (e.g. cocktail party). How does the brain transform this barrage of signals into a coherent percept of the environment?
- Audiovisual integration of naturalistic (e.g. speech) signals
- How do attention and expectations influence multisensory processing?
- How does the brain adapt multisensory processing to a changing world at multiple timescales?
- Which factors determine inter-trial and inter-subject variability in multi-sensory integration?

Relevant literature:

1. Gau R, Trampel R, Bazin PL, Turner R, Noppeney U (2020) Resolving multisensory and attentional influences across cortical depth in sensory cortices. *eLife*. e46856. doi: 10.7554/eLife.46856.
2. Rohe T, Ehlis AC, Noppeney U (2019) The neural dynamics of hierarchical Bayesian causal inference in multisensory perception. *Nat Commun*. 10(1):1907.
3. Aller M, Noppeney U (2019) To integrate or not to integrate: Temporal dynamics of hierarchical Bayesian Causal Inference. *Plos Biology*. 17(4):e3000210.
4. Rohe T, Noppeney U (2016) Distinct computational principles govern information integration in primary sensory and association cortices. *Current Biology*. 26(4):509-14.
5. Rohe T, Noppeney U (2015) Cortical hierarchies perform Bayesian Causal Inference for multisensory perception. *PLOS Biology*. 13(2):e1002073.

If you are interested please get in touch: *u.noppeney@donders.ru.nl*

Making sense of the senses

How does the brain integrate noisy sensory signals to create a coherent percept of the world?

When we listen to someone talking, we hear their voice and see their mouth move – separate sensory signals that the brain combines to make sense of speech. Yet this integration, and determining what sensory signals belong together and which should be kept apart, is no trivial matter – as the research of **Uta Noppeney** in Birmingham has revealed.

Professor Noppeney initially studied medicine and philosophy. She was particularly interested in Kantian philosophy, and the work of 20th-century neurologist and psychiatrist Kurt Goldstein: "What he was interested in was basically what I am still interested in – how the brain structures all the sensory inputs we're confronted with into a coherent percept of the world."

After training in neurology, Professor Noppeney undertook a PhD at the Wellcome Centre for Neuroimaging in London, before moving to Tübingen, Germany. Here, she settled on the big question she is still trying to address: "You're bombarded with all these sensory signals, visual signals, auditory signals, and so on – how does the brain transform this sensory cacophony into a coherent percept of the world?"

Sight and sound

A key challenge for the brain is uncertainty: "All our senses provide us with complementary information about the world," points out Professor Noppeney. "But sensory signals are corrupted by noise from the external world and our neural system." Combining information from different sources should, in theory, give us a better picture: "If we integrate information across the senses, we should be able to reduce our uncertainty about the world."

The basic idea is to treat perception as probabilistic inference based on noisy sensory measurements of the world. This way of thinking goes back to Helmholtz's idea of unconscious inference and underlies psychophysics and computational models of perception. Complementing this approach, neuroimaging has been used to identify the neural mechanisms of perception. "What we were trying to do is bridge between behaviour, computations and neural mechanisms," says Professor Noppeney.

The psychophysics approach draws upon a Bayesian framework, whereby probabilistic computations are used to interpret noisy information. "Bayesian probabilistic models can define a benchmark of what an optimal or ideal observer should be doing in order to get a reliable percept of the world. It's a benchmark to compare human observers with."

Indian ventriloquist Ramdas Padhye with his puppet Ardhavatrao.

At a glance

- The brain must combine noisy information from multiple senses to create a coherent experience of the world.
- The brain may use Bayesian moedlling to process sensory information according to its reliability.
- Neuroimaging has revealed a hierarchy of brain structures involved in the processing and integration of sensory information.

After long years of winnowing by natural selection, humans should be pretty good at generating an accurate picture of the outside world. And studies in which people have to locate events or objects, based on auditory and visual information, suggest that we operate at least in simple situations approximately in a Bayesian way. When integrating signals, we give more weight to those inputs that are more reliable – our sight, for example, is generally a more precise estimator of location than our hearing. "It makes sense – at a court trial, if you have multiple testimonies, you would also give more weight to the testimonies of people who are reliable."

Part of Professor Noppeney's programme of work is based on understanding how the brain carries out these computations. She applies Bayesian models not only to observers' behaviour but also directly to neural activity or representations decoded from activation patterns to identify the computational principles that govern multisensory integration in the brain – such as in areas where sensory signals are integrated according to their reliability.

To bind or not to bind

A second key area of interest is the 'binding problem', the question of how the brain decides that signals from two senses derive from the same source – a person speaking, for example – or from separate sources.

"In a complex world you need to bind signals that come from a common source, but segregate signals that come from independent sources. In a busy pub you shouldn't bind the clinking of the glasses or the laughter at the neighbouring table when you're trying to understand the person sitting next to you."

Fundamentally, therefore, the brain has to decide whether to integrate or to segregate. Here again, these processes have been modelled using a Bayesian approach, through a Bayesian causal inference model – which explicitly models the causal structure that could have generated signals (such as a common source or separate sources). The brain has to infer the probabilities of these different causal structures, generating probabilistic estimates for each. "To account for your uncertainty about the causal structure of the world, you should then combine these different estimates according to some decision function – for instance weighted by the probabilities of each causal structure."

Neuroimaging studies have provided insight into how the brain implements these computations. "We observed that the brain accomplishes Bayesian causal inference by computing multiple perceptual estimates dynamically along the cortical hierarchy." First up, primary sensory areas represent location independently for sight and sound. Then, higher-order areas in the parietal cortex integrate signals weighted by their reliabilities, but without considering task relevance and causal structure. Finally, anterior parietal areas perform the Bayesian causal inference – arbitrating between sensory integration and segregation and combining signals into spatial priority maps to guide behaviour.

Notably, the brain sometimes gets it wrong – which forms the basis of perceptual illusions. By manipulating the spatial disparity of beeps and flashes, yet presenting them in synchrony, researchers can make it appear that visual and auditory signals are co-located when they are not – the ventriloquist's illusion. "You trick the brain into thinking these two signals are coming from a common source, because they are happening in synchrony, so you integrate them." As sound is usually spatially less reliable than vision, a puppeteer's vocalisations are mislocated to the puppet. Something similar enables us to perceive dialogue from a movie screen as coming from an actor, even when the loudspeakers are at the side of the theatre.

"YOU'RE BOMBARDED WITH ALL THESE SENSORY SIGNALS, VISUAL SIGNALS, AUDITORY SIGNALS, AND SO ON – HOW DOES THE BRAIN TRANSFORM THIS SENSORY CACOPHONY INTO A COHERENT PERCEPT OF THE WORLD?"

Complexities and constraints

Having looked at brain responses to simple visual and auditory cues, Professor Noppeney is keen to explore more real-life situations: "I am interested in how the brain makes inferences in more naturalistic environments with multiple sources and complex time-varying signals that provide multiple different correspondence cues." For instance, for interpretation of speech in a busy pub, the brain has to deal with visual and auditory inputs, and higher-order spatiotemporal patterns – and also integrate linguistic information.

Likewise, the dynamics and temporal constraints of our natural environment pose new challenges for perceptual inference. In laboratory experiments, participants often have unlimited time to arrive at decisions, but in the real world speed can be critical. "When crossing the street, you do not only want to accurately locate the lorry – you need to move out the way before it hits you." All these situations make multisensory perception computationally very demanding. A key question for Professor Noppeney's future research is therefore how the brain, with its limited resources, computes approximate or even just heuristic solutions in these more challenging situations.

She is also keen to explore perceptual processing in people with neuropsychiatric disorders such as autism spectrum disorder. Such people show perceptual abnormalities, including different susceptibility to perceptual illusions. However, research to date has mostly been descriptive. "I would like to combine psychophysics with computational models and neuroimaging to move beyond phenomenological research and understand better how their perceptual inference and learning may differ."

British Library

A poster for a performance by Miss Madeline Rosa, ventriloquist.

Professor Noppeney hopes that research will eventually provide the answers to these questions. "Philosophy and neuroscience, at times, ask similar questions but with very different perspectives," she suggests. Often, philosophical interests grow as scientists get older. "I seem to have done it the other way round!"

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