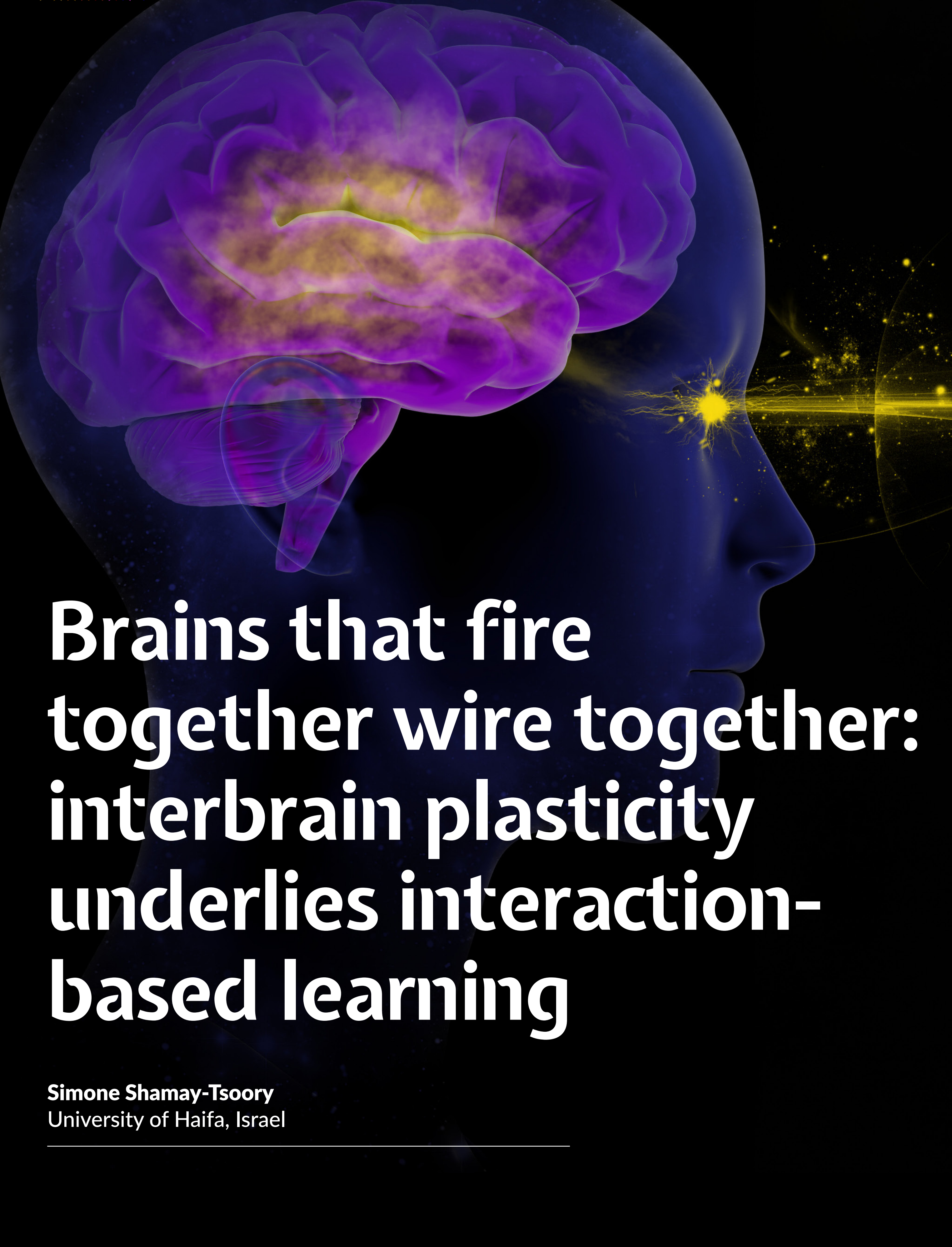

Brains that fire together wire together: interbrain plasticity underlies interaction-based learning

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As we learn, our brain reorganises its structure, functions and connections. Brain plasticity represents the remarkable capacity for the brain to change its activity in response to experiences. Yet, despite the immense developments in the field of brain plasticity, the bulk of research in the field is deeply rooted in understanding experience-driven neural changes of individuals, isolated from any social context. Nevertheless, immeasurable knowledge is acquired through social interactions. We learn about the social world and acquire motor skills and languages by interacting with other individuals.

The question remains: why do we learn in social interactions? There are several reasons why learning should be poorer in social interactions compared to no interaction. First, the interaction itself can require monitoring of bidirectional responses that may increase cognitive load and interfere with learning. Second, emotional reactions such as fear of performing improperly or being evaluated negatively may impair learning. Yet studies show that people learn better when they interact as compared to no interaction. The benefits of interaction-based learning may be explained by the mutual alignment that develops between the interaction partners in a way that allows for 'personalised' transfer of knowledge. Social alignment is a dynamic two-way process of coordinating behaviour. When learning through social interactions, information about the acquired knowledge, as well as about the interaction partner, is transferred. Therefore, during interaction-based learning, changes are expected to occur not only in brain networks specific to the acquired skill but also in networks related to social alignment.

Notably, in recent years new neuroimaging techniques have been used to measure brain activity from two or more individuals simultaneously, allowing the assessment of moment-to-moment brain-to-brain coupling during social interactions. These studies indicate that brain regions not only hold the capacity to coordinate their activity *within* a brain (creating intra-brain networks) but also coordinate their activity *between* brains during social communication. *Brain-to-brain coupling* denotes correlation in brain activation between regions of two interacting brains. While intra-brain coupling is assumed to be mediated by anatomical connections, the brain-to-brain coupling may be mediated by sensorimotor signals.

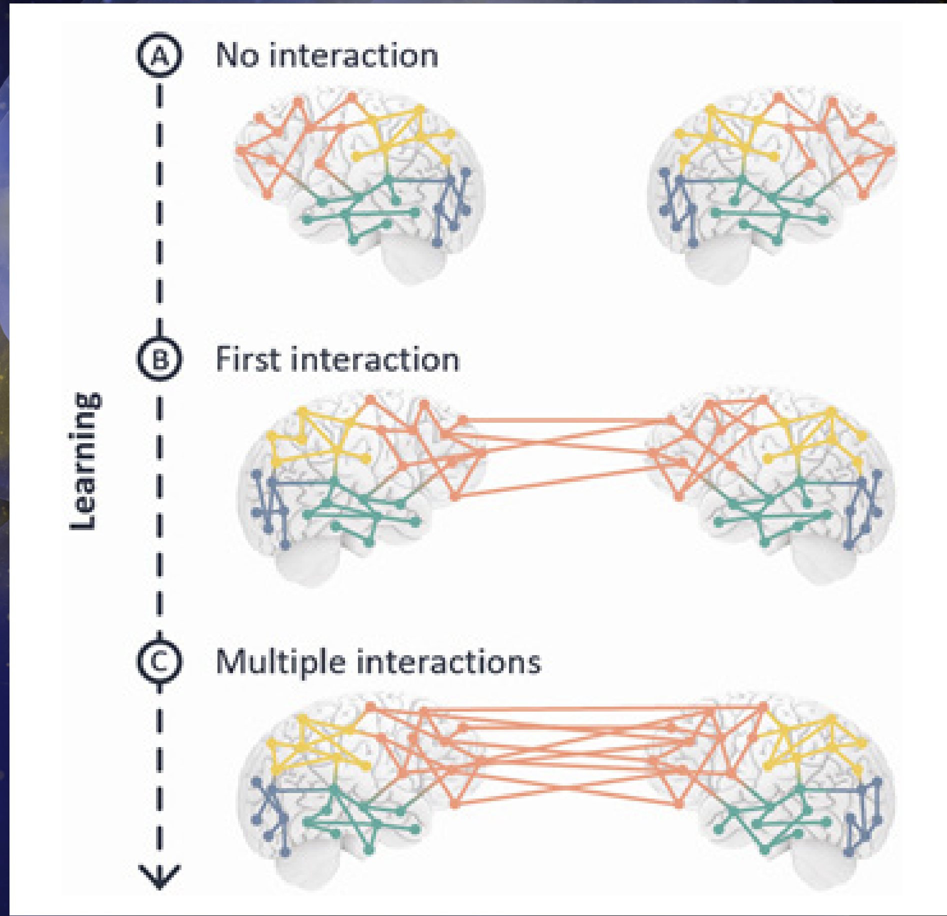

Figure 1: Schematic illustration of inter-brain plasticity. Intra- and inter-brain networks reconfigure following IBL.

Studies with dual-functional near-infrared spectroscopy (fNIRS) show that some brain regions of interacting individuals are not only active in one individual but also show brain-to-brain coupling (correlation) between individuals during social alignment. For example, it was found that brain-to-brain coupling between the frontal regions, previously implicated in imitation of interacting individuals, is evident during tasks that involve cooperation, synchronisation and even song learning. Notably, in a recent dual-EEG study, we showed that brain-to-brain coupling in the alpha/mu band (8–12 or 13 Hz), considered to be a biomarker of the mirror neuron system, is linked with empathy.

The findings of brain-to-brain coupling during social interactions have greatly advanced neuroscience as they showed that multiple brains of interacting individuals can be viewed as components of an extended network in which nodes represent different brain regions of different individuals and edges represent between-brain connections. Furthermore, diminished brain-to-brain coupling was reported in individuals with autism spectrum disorders (ASD), further indicating that measures of brain-to-brain coupling may also have a clinical value. Critically, brain-to-brain coupling was shown to yield higher predictive power for learning outcomes than single-brain measures, emphasising the importance of incorporating these measures in social behaviour models.

Despite these exciting developments, the question remains whether, similarly to intra-brain networks, inter-brain networks are *plastic* and may reorganise following repeated training. While the studies to date view brain-to-brain coupling as a transient coupling that occurs during interactions, the INTERPLASTIC project will enable probing the *short and long-term experience-dependent changes in brain-to-brain coupling* for the first time. This new frontier of investigations goes beyond measuring inter and intra-brain networks at a given time to examine how inter-brain networks change following repeated training.

To establish the inter-brain plasticity theory, I will carry out a set of experiments that will examine the reconfiguration of inter-brain networks during interaction-based learning. To this end, I will take advantage of the high temporal resolution of state-of-the-art dual-functional fNIRS set up and examine how intra- and inter-brain networks reconfigure during learning of various skills, ranging from motor learning to language acquisition.

In one experiment, for example, I will examine inter-brain plasticity in teacher-learner interactions, with a novel designed one-way mirror set up, which allows the direct comparison of bidirectional (both the learner and the teacher see each other) and unidirectional learning (when only the learner sees the teacher), with a high level of controllability. I plan to examine the contribution of inter-brain plasticity to bidirectional as compared to unidirectional training in a paradigm of learning sequences of Tai Chi movements.

After establishing the inter-brain plasticity model, I will examine a novel approach that allows drawing causal inferences between inter-brain plasticity and behaviour. It is unclear whether brain-to-brain coupling could be trained and to what extent training is translated into improved learning.

Neurofeedback is a technique that provides real-time information about the current level of brain activity, to which we otherwise do not have conscious access. Such information can be used to learn the volitional regulation of brain activity. The feedback is visual or auditory (e.g. an animated fish swimming in the sea [Figure 2]), in which changes in certain parameters (e.g. the fish's movement) reflect changes in certain features of the measured brain activity. Increasing evidence demonstrates trainability of the hemodynamic response as assessed with fNIRS during neurofeedback, suggesting that it is an attractive method for neurofeedback. Here I propose to develop and validate a novel fNIRS *dyadic neurofeedback platform* intended to allow participants to control their brain-to-brain coupling by giving them feedback on this coupling. Therefore, the dyadic neurofeedback platform will pave the way for limitless future work aimed at controlling brain-to-brain coupling. With respect to basic science, it will provide a causal link between brain-to-brain coupling and interaction-based learning. Its practical applications are numerous and may include training inter-brain plasticity in populations showing poor interaction-based learning, including individuals with ASD).

Figure 2: Illustration showing neurofeedback where feedback is visual, in this case changes in movement of an animated fish.

In the final stages of the project, we will focus on characterising inter-brain plasticity in individuals diagnosed with ASD. If deficits in inter-brain plasticity do indeed underlie poor interaction-based learning in ASD, it is possible that training individuals with ASD to become coupled in their brain activity with typically developing individuals would improve their ability to learn in interactions. It is possible that training individuals with ASD to better align with one partner will generalise better alignment with other partners. Previous behavioural studies have shown improved behavioural synchrony after treatment for individuals with ASD, suggesting that their capacity to synchronise can improve. Considering that the behavioural difficulties of individuals with ASD are primarily observed during real-life social interactions, training their intra-brain activity, as done in conventional neurofeedback, may not be the optimal intervention for these individuals. To examine how modifiable is inter-brain plasticity in ASD, I will use the new dyadic neurofeedback platform to train individuals with ASD to control their inter-brain plasticity. Training individuals with ASD with the dyadic neurofeedback platform may have important clinical implications for ameliorating social deficits in these individuals.

The INTERPLASTIC project may lay the foundation for a new field of research focusing on inter-brain plasticity. This field could develop into multiple paths, from testing inter-brain plasticity in various learning contexts as well as in psychopathology, during psychotherapy, in romantic relationships, in educational settings and more. The new neurofeedback technology will have an array of uses we can only begin to imagine. With respect to basic science, it will make attempts to establish the first causal link between inter-brain plasticity and learning possible. Its clinical benefits include interventions for improving social alignment during interactions.

PROJECT NAME
INTERPLASTIC

PROJECT SUMMARY
Even though social interactions are significant determinants of learning, the field of neuroplasticity doesn't take this into account. Instead, it is deeply rooted in probing changes occurring in synapses, brain structures, and networks within an individual brain. The ERC funded INTERPLASTIC project, however, will propose a new approach that synthesises disparate findings on network neuroplasticity and mechanisms of social interactions. It will test whether the facilitation effect of social interactions on learning can be explained by interbrain plasticity (short- and long-term experience-dependent changes in interbrain coupling).

PROJECT LEAD PROFILE
Simone Shamay-Tsoory is Professor of Psychology at the University of Haifa, Israel. Her work seeks to understand the neural mechanisms underlying social behaviour and in particularly empathy. To address these issues she works with various populations of patients as well as with healthy individuals and uses neuroscience tools including neuroimaging, neurostimulation and psycho- pharmacological techniques. Senior Researcher, Brain Activity Project.

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