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# COMMENTARY

# Hyperscanning: Simultaneous fMRI during Linked Social Interactions

P. Read Montague,* Gregory S. Berns,† Jonathan D. Cohen,‡ Samuel M. McClure,* Giuseppe Pagnoni,† Mukesh Dhamala,† Michael C. Wiest,* Igor Karpov,* Richard D. King,* Nathan Apple,* and Ronald E. Fisher*

**Center for Theoretical Neuroscience, Division of Neuroscience, Baylor College of Medicine, Houston, Texas 77030; †Department of Psychiatry & Behavioral Sciences and Biomedical Engineering, Emory University School of Medicine, Atlanta, Georgia 30322; and ‡Department of Psychology, Center for the Study of Mind, Brain, and Behavior, Princeton University, Princeton, New Jersey 08540*

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"Plain question and plain answer make the shortest road out of most perplexities."

Mark Twain-*Life on the Mississippi*

**A new methodology for the measurement of the neural substrates of human social interaction is described. This technology, termed "Hyperscan," embodies both the hardware and the software necessary to link magnetic resonance scanners through the internet. Hyperscanning allows for the performance of human behavioral experiments in which participants can interact with each other while functional MRI is acquired in synchrony with the behavioral interactions. Data are presented from a simple game of deception between pairs of subjects. Because people may interact both asymmetrically and asynchronously, both the design and the analysis must accommodate this added complexity. Several potential approaches are described.** © 2002 Elsevier Science (USA)

## INTRODUCTION

Social interactions among humans are a central feature of cognition. However, the neural substrates that underlie how people interact with one another are virtually unknown. Some progress in identifying brain structures involved in social interactions has been made (Frith and Frith, 1999), but we have little knowledge of the patterns of neural activation that drive social exchanges. There are two primary reasons for this gap in our knowledge: (1) social interactions can be exceedingly subtle and complex and (2) there has been no enabling technology that permits the simultaneous monitoring of socially interacting brains.

Social psychologists and anthropologists have provided insight into the range and variety of social interactions expressed by humans. Some approaches use informed guesses about our ancestral environs and the kinds of social mechanisms required to be reproductively successful in such settings (e.g., Duchaine *et al.*, 2001). Other approaches focus on the complicating factor of culture and its interaction with genetically inherited, highly adaptable social mechanisms. Even a casual reading in these literatures demonstrates the tremendous scale of the problems. Nevertheless, if one wants to make inroads into the neural basis of social interactions, the plain approach is clear: let humans interact socially while concurrently probing their brain activity.

In this commentary we outline both the virtues and the problems associated with such an approach where our neural probe of choice is functional magnetic resonance imaging (fMRI). Our approach is simple: let humans interact in a controlled setting while their brains are simultaneously scanned. We have called such simultaneous scanning hyperscanning.

## THE ADVANTAGES OF HYPERSCANNING

Why study interacting humans while simultaneously scanning their brains? One could instead design social interaction tasks with one person inside and one person outside a scanner. The two subjects could interact through a computer link while one subject's brain is scanned. Afterward, the two subjects could switch places and the task could be repeated. This method can and has produced useful results. However, this type of experiment will detect only brain activity that correlates with an observable behavior that can be used as a fiducial marker in the analysis. Such a reference marker will be necessary to reliably detect the activity, to evaluate its possible social significance, and to average it across subjects or across multiple trials of the same subject. Hyperscanning, in contrast, requires no such behavioral marker—quite an advantage, since



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much of the brain activity that occurs during an interaction may not correlate with detectable behavior. During one moment, for example, the two subjects might be simultaneously engaged in guessing what the other person is thinking, but it would be nearly impossible to uncover this brain activity in the murky, continuous stream of fMRI signals and to correlate it with anything. With hyperscanning, this sort of activity might reveal itself as a regional pattern of activity in one brain that is consistently correlated with similar activity in the other brain.

This view of the utility of hyperscanning relates to a broader view of the nature of neural responses underlying social exchanges between humans. The neural basis of a social interaction is a dynamical relationship between activity in one brain and activity in another. Indeed, social behavior could be regarded quite simply as what happens when two brains try to detect and influence what the other is doing. The possibility of observing activity in a large number of voxels in both brains while they interact opens up truly new scientific possibilities. Behavioral channels are intrinsically low-bandwidth channels: a person sweats more, glances left or right, increases pupillary dilation, and so on. In contrast, the underlying neural events are intrinsically high dimensional, and the possibility of searching directly for correlations in neural activity between socially engaged brains will increase the chance of finding important underlying neural relationships and could spawn new approaches to understanding the neural basis of social exchanges. Studying social interactions by scanning the brain of just one person is analogous to studying synapses while observing either the presynaptic neuron or the postsynaptic neuron, but never both simultaneously. Imagine that one were limited to stimulating and observing the presynaptic neuron and then later stimulating and observing the postsynaptic cell: One could laboriously study each for years without discovering that activity in the presynaptic neuron induces activity in the postsynaptic cell and might never come to an accurate description of synaptic transmission, let alone that of the many forms of synaptic plasticity. Synapses, like socially interacting people, are best understood by simultaneously studying the interacting components.

## LINKED EXPERIMENTS

Before detailing our specific preliminary efforts using hyperscanning, we first outline two models for using behaviorally and biometrically linked experiments. Figure 1A shows one general way in which behavioral interactions and biometrical assays can be linked. The links that we present below are accomplished through the internet; however, any reliable communication channel would suffice. In this example, some kind of social exchange experiment is taking place. The synchronized behavioral channel links the behavioral outputs and inputs of the two participating subjects. This linkage is implemented in parallel to the other channel that synchronizes the biometrical assay in each participant. In other words, two (or more) subjects are permitted to interact socially, for example by sending each other visual or auditory messages or by sending each other squirts of juice. Simultaneously, their brains are being scanned, but their behavior is not affecting how the fMRI scans (the biometrical assays) are conducted, and similarly the fMRI results are not influencing their behavioral inputs and outputs.

Below, we have used the simplest incarnation of this setup to carry out a social exchange task during simultaneous fMRI. This represents an experiment where the behavioral inputs and outputs are tightly linked, but the biometrical assays are simply started at the same time and allowed to run in parallel.

An interesting and powerful arrangement for a linked experiment is shown in Fig. 1B. Here, the biometrical channel and the behavioral channel feed information to one another. For example, each subject simultaneously may view a nearly real time, continuous fMRI scan of the other subject's brain. By controlling juice delivery or visual or auditory presentations, each subject may attempt to influence the activation of the other's brain. This arrangement allows a fully linked social exchange experiment to take place, where both behavioral and biometrical events feed to the other channel and influence its state. Such an arrangement would allow for a wide array of experiments. We have not yet attempted this type of hyperscan experiment. However, we do have some preliminary data on a simple form of hyperscanning, which is described below.

## A SIMPLE LINKED EXPERIMENT: SIMULTANEOUS fMRI DURING A PACED SOCIAL EXCHANGE

We performed simultaneous fMRI in different scanners with pairs of individuals competing against each other in a simple game. The architecture of this arrangement was designed to operate over the internet and to be scalable to $n$-player games (Figs. 2 and 3). The game was designed to measure the effect of deception in a competitive context. The game is a variant of an old children's game known as "handy-dandy." In handy-dandy, player 1 conceals an object in either hand, and player 2 must guess in which hand the object resides.

Our game was analogous, but had the added element of conscious deception. Player 1 (sender) sees either a red or a green screen and chooses to transmit either red or green to player 2 (receiver) by pressing one of two buttons in an optical button box. Player 2 either agrees with the color sent (guesses that player 1 tells the truth) or disagrees (guesses that player 1 lied). If the receiver correctly guesses the color that the sender viewed, then the receiver wins; otherwise the sender wins. The winner receives a squirt of juice in the mouth at a prespecified time (Fig. 3). The game was temporally paced so that the events occurred at designated points in time, and one round lasted 25 s (Fig. 3). After 13 rounds, which corresponded to one functional scan run, the sender and receiver reversed roles and played again.

Separate client computers mediated the interaction for each player. They were responsible for (1) producing the player's visual display, via an LCD projector directed into the magnet bore, (2) monitoring the player's response through fiberoptic response devices input into the serial port, and (3) communicating with a server via high-speed ethernet connection. A server computer coordinated the timing of the game for both players, collected packet latency statistics during the task, kept a canonical clock for subsequent synchronization of the scans and behavioral events, and controlled the delivery of juice to the players by sending time-stamped commands to the client computers that issued commands to the juice pumps. All software was original, developed by the Hyperscan Development Group (see www.hnlsource.org and www.hyperscan.org), and written in Java for maximum portability.

Simultaneous fMRI was performed on two Philips ACS 1.5 T scanners. A standard sequence was used for gradient-recalled echo-planar imaging of the blood oxygen level-dependent (BOLD) effect (Kwong *et al.*, 1992; Ogawa *et al.*, 1992), which yielded 154 whole-brain images per round for each player (single-shot GRE EPI; TR = 2000 ms; TE = 40 ms; flip angle = 90°; $64 \times 64$ matrix; 24 5-mm axial slices; FOV = 240 mm). Three pairs of different subjects were scanned. Each pair played the game twice during the fMRI session: after the first imaging run was completed, the players switched role (sender and receiver) and a second imaging run was collected.

Functional scans were subsequently corrected for head motion using a six-parameter rigid body transformation using SPM99, masked to include only gray matter voxels, and temporally filtered to remove low- and high-frequency noise. A "hyperbrain" was formed by the spatial concatenation of both functional datasets; that is, each row of the data matrix represented one point in time, but was composed of the gray matter voxels from both subjects. Two different types of analyses were performed on the hyperbrain. First, independent components analysis (ICA) was performed on this hyperbrain with retention of the 135 largest components using the Fast ICA algorithm (Bell and Sejnowski, 1995; McKeown *et al.*, 1998; Hyvarinen, 1999). ICA decomposition of the concatenated hyperbrain allowed for the separation of both individual activity modes and interacting modes. The time courses associated with each mode were cross-correlated with time series obtained from the behavioral data. Specifically, we examined the time course of juice delivery to the two players, hypothesizing that this would be a salient event for both subjects with the winner and loser showing opposite responses.

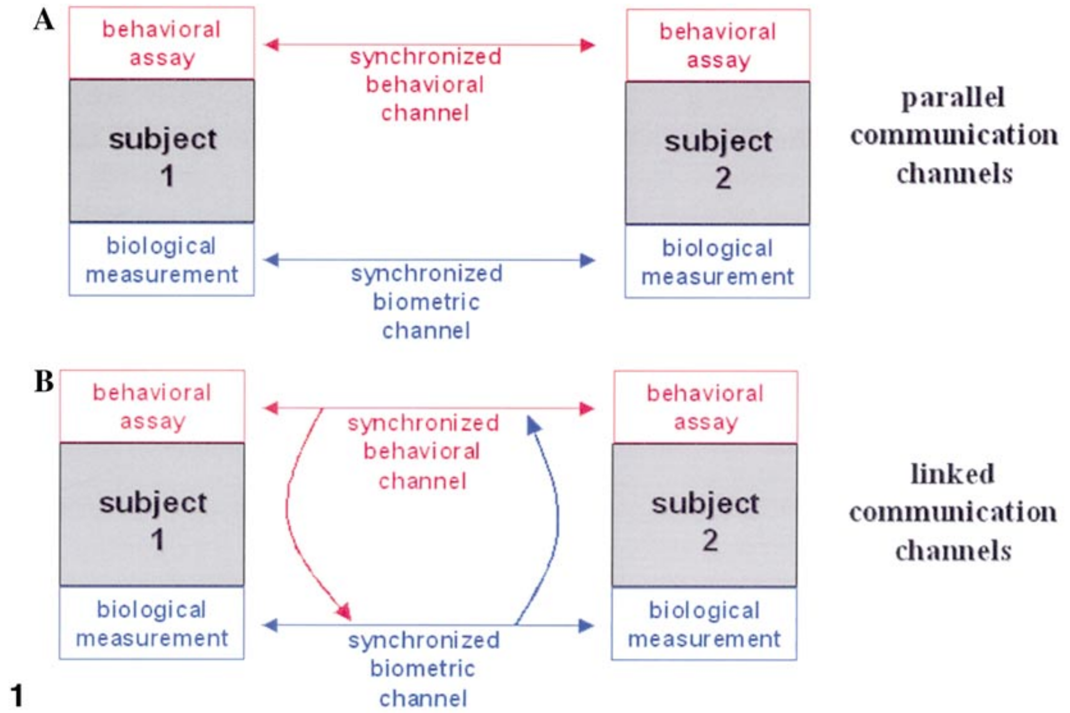
Second, to address the issue of asynchronous information exchange between individuals, we also examined the cross-spectral coherence of the different modes of activity in each individual (Nunez, 2000) (Fig. 3B). Using singular-value decomposition, we retained the 20 largest components of each individual's dataset. We then computed, for each time course against each other, the cross-spectral coherence based on estimation of the spectral density (Welch, 1967). This allowed the identification of frequency bands containing most of the power or those showing task-dependent changes. We focused our attention on the frequency band centered at 0.04 Hz, which corresponded to the base period of the game (25 s). The coherence measures the degree of common power between two signals at a particular frequency and quantifies the functional coupling between those signals at that frequency, independent of phase.

This experiment is clearly preliminary and exploratory, but it demonstrates that hyperscanning experiments are feasible despite the complications that arise in using two or more scanners simultaneously. However, significant technical hurdles still exist to further extend this approach. We outline some of the issues below.

## TECHNICAL AND CONCEPTUAL CHALLENGES FOR HYPERSCANNING EXPERIMENTS

### *Interscanner Variability*

The performance of hyperscan experiments requires that different scanners be linked together. Most fMRI studies are conducted on a single scanner and do not need to account for operating characteristics among different scanners. Even at the same field strength, different scanners may have different gains, different gradient strengths, head coil sensitivities, shimming protocols, etc. The growing installation of higher field scanners raises the possibility of linking together scanners with different main fields, and this will add to the intersite variance. All of these factors will have varying effects on the quality of the data that emerges from each participant in a hyperscan experiment. A few studies that have compared fMRI at different sites have found comparable results (Casey *et al.*, 1998), but none of this work has sought to characterize signal variability associated with two subjects during simultaneous scanning. In a hyperscan experiment, each subject at each site may carry unique information that could be lost in the noise if the signal quality from a particular site was poor. One solution for intersite scanner variance is the inclusion of well-characterized MR phantoms at each participating site that could provide a model for sources of variance at each participating site during each experiment. As described be-



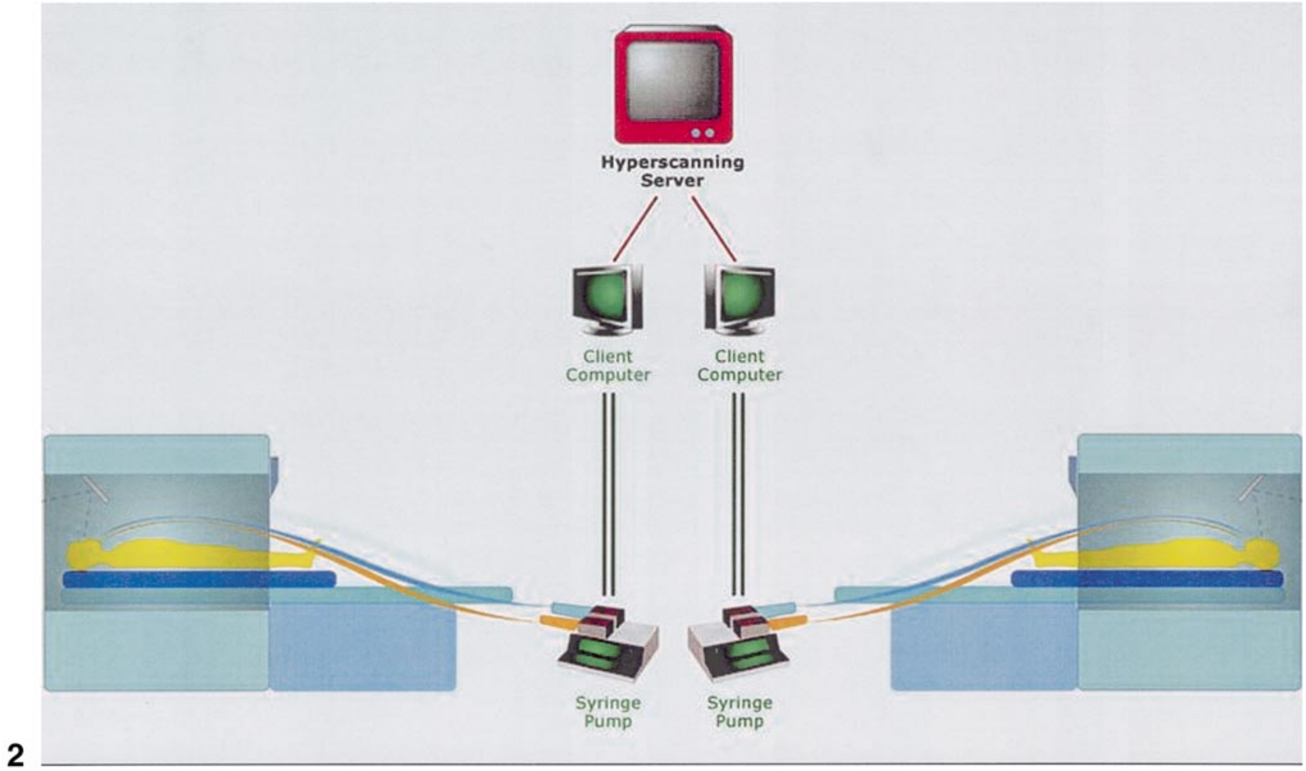




**FIG. 1.** General models for linked experiments. (A) Parallel communication channels permit linked behavioral and biometrical interactions, but there is no interaction between the channels. An example of such an arrangement is illustrated in Fig. 2 and described in the text. (B) Fully linked social interaction experiment. Events in both the behavioral and the biometrical channels can influence events in the opposite channel. For example, the scan of subject 2's brain could be dynamically displayed in some form to subject 1. Subject 1 could then choose behavioral outputs with the intent of causing certain patterns of activation in subject 2's brain.

**FIG. 2.** Setup for hyperscan: simultaneous fMRI Client computers control presentation of stimuli, including delivery of juice squirts to subjects' mouths. The clients communicate with one another through a server, which retains control of the entire experiment. In the experiment described in the text and illustrated in Fig. 3, the fMRI scans were simply started at the same time; there was no communication between the behavioral interaction and the scanning. In a fully synchronized hyperscan experiment, there would be two-way communication between the biometric (here fMRI) and the behavioral channels.

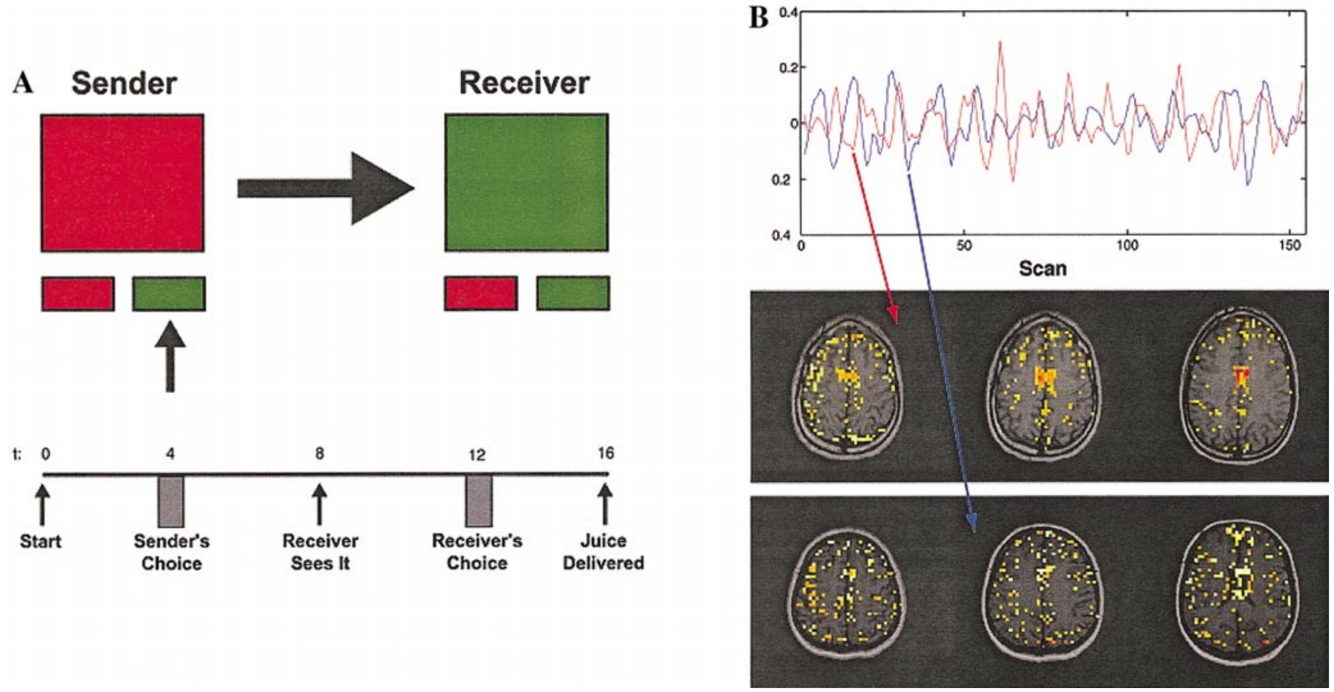



**FIG. 3.** Prototype hyperscanning experiment. (A) A simple deception task was used. One player, designated the "Sender," saw either a red or a green screen. They then transmitted either red or green to the "Receiver," who then had to decide what the Sender actually saw. If the Receiver guessed correctly, he was rewarded with a small squirt of fruit juice in the mouth; otherwise the Sender received the juice. Thirteen rounds were played and the roles reversed. (B) An example of a mode of activity in both the Sender and the Receiver brains with coherent power at the base frequency of the task (0.04 Hz). Three slices through a singular-value decomposition mode in both the Sender and the Receiver are shown with their corresponding time courses above. These two modes had the greatest coherence in the 0.04-Hz frequency band. Pixels correlated with their respective timecourses are shown ($r > 0.3$). In both the Sender and the Receiver, a cluster of activity is identified in the region of the supplementary motor area, but this is stronger in the Sender than in the Receiver (arrows). Examination of the respective time courses of these two modes showed a general temporal coherence but with slight changes in the relative phase during the course of the experiment.

low, we also favor the inclusion of standard tasks or stimuli at the beginning of each hyperscan experiment to calibrate both the scanners and the subjects at the time of each experiment.

*Analysis and Small Sample Noise*

There are many sources of variability in any fMRI experiment, and this problem is only compounded in a hyperscan experiment. In the general case, hyperscanning imposes a technical signal-to-noise problem because of the need to extract a meaningful signal from a pair of interacting individuals. There is no obvious or straightforward way to average over pairs, triples, or *n*-tuples of interacting subjects; therefore, neural responses, as assessed during repeated bouts of the social exchange must be extractable from a significant amount of noise. While this represents a problem, it is not insurmountable. We believe that online noise estimation will soon be possible and will serve to meliorate partially the problem of small sample size. One idea that we are actively investigating is to use periodic sensory stimuli (contrast-modulated lights, taps to small dermatomes, etc.) to drive spatially localized activation in a small group of voxels. This could establish periodic activation in small brain regions not activated by particular elements of a social exchange under study. This approach could be used to extract a model of the noise in the activated voxels, and this model could be dynamically deconvolved during an experiment. This approach represents an extension of work using the visual response as a time marker for the prefrontal response (Menon *et al.*, 1998), and it depends on a number of factors to be successful, but an off-line version of it would also be helpful in increasing the signal-to-noise ratio.

The analysis of hyperscanning datasets also presents a unique challenge that embodies many of the usual problems associated with fMRI but adds some new ones also. The hyperbrain data presented earlier highlight this point. At the simplest level, one can analyze these data with parallel univariate statistics using conventional general linear models (GLM), as are commonly implemented in widely available packages. This approach has the advantage of using well-characterized statistical methods and would be most appropriate for experiments with a limited number of event types that could be entered into a general linear model. For example, in a two-person experiment with two possible responses from each subject, this could be analyzed as a $2 \times 2$ factorial with main effects of subject and response and an interaction term.

In many hyperscanning experiments the GLM approach may be inappropriate either because there are too many event types or because the events are not generated independently. In other cases, the definition of an event boundary may be unknown. In these cases, more exploratory, or data-driven, approaches can be useful. Principal components analysis (PCA), independent components analysis, and partial least squares (PLS) are all methods that can identify correlated modes of activity in individual brains that are easily extended to hyperbrains. However, even data-driven approaches such as PCA and ICA will not identify temporally dynamic processes that might be integral to any social exchange. Linear decompositions can identify only activity modes that are temporally correlated. One important issue that also arises is how to appropriately weight each subject's brain. Although not shown here, our current approach to this weighting is to use a version of the noise-building model above to estimate a signal-to-noise ratio for each brain in a hyperbrain ensemble. Each component brain is then weighted according to its estimated signal-to-noise ratio.

### *Internet Latencies*

Another important confounding influence on hyperscanning experiments is the distribution of latencies through the internet. There are many aspects of any behavioral exchange that cannot withstand latencies that vary significantly. The most important issue here is not the fact of latencies, but the stability of the distribution of latencies. Here we mean the time for a message generated at one client to reach the other client. In the current task and in simulated hyperscan experiments over the internet, we have not encountered significant problems with latencies. In scenarios tested so far, the latencies fall well under 300–400 ms and therefore escape being a problem for many behavioral tasks in which interactions are much longer. The latency and duration of the BOLD response remain by far the larger constraint on the types of tasks that could be reasonably carried out using hyperscanning.

## FINAL THOUGHTS

The availability of new web-based computing technologies allows for a new generation of fMRI experiments. The possibility of measuring important biological substrates of human social interaction is now made real by the feasibility of truly distributed computer code and its capacity to link experimental interactions over the web. The number of possible uses of such a technology exceeds both our space in this commentary and our collective ability to exploit the technology. It is the goal of the hyperscan consortium to make all the fundamental software components available through an open source model. We welcome feedback, criticism, and help.

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