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Leveraging Social Networks for the Assessment and Management of Neurological Patients

Amar Dhand, MD, DPhil[1] Archana Podury, BA, MD[2] Niteesh Choudhry, MD, PhD[3]
Shrikanth Narayanan, PhD[4] Min Shin, PhD[5] Matthias R. Mehl, PhD[6]

[1] Brigham and Women's Hospital, Harvard Medical School, Network Science Institute, Northeastern University, Boston, Massachusetts
[2] Harvard-MIT Health Sciences and Technology Program, Harvard Medical School, Boston, Massachusetts
[3] Harvard Medical School, Health Policy and Management, Harvard T. H. Chan School of Public Health, Boston, Massachusetts
[4] Department of Electrical and Computer Engineering, University of Southern California, Los Angeles, California
[5] Department of Computer Science, University of North Carolina at Charlotte, Charlotte, North Carolina
[6] Department of Psychology, University of Arizona, Tucson, Arizona

Address for correspondence Amar Dhand, MD, DPhil, Brigham and Women's Hospital, Harvard Medical School, 65 Landsdowne Street, Cambridge, MA 02139 (e-mail: adhand@bwh.harvard.edu).

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Abstract

Social networks are the persons surrounding a patient who provide support, circulate information, and influence health behaviors. For patients seen by neurologists, social networks are one of the most proximate social determinants of health that are actually accessible to clinicians, compared with wider social forces such as structural inequalities. We can measure social networks and related phenomena of social connection using a growing set of scalable and quantitative tools increasing familiarity with social network effects and mechanisms. This scientific approach is built on decades of neurobiological and psychological research highlighting the impact of the social environment on physical and mental well-being, nervous system structure, and neuro-recovery. Here, we review the biology and psychology of social networks, assessment methods including novel social sensors, and the design of network interventions and social therapeutics.

Keywords
- social connection
- social networks
- psychosocial interventions
- neurobiology
- neuropsychiatry
- mobile sensing

In many instances, the social environment can be more important than biology in determining health outcomes. Socioeconomic factors and health behaviors contributed 81% to health outcomes in one nation-wide study.[1] Clinical care, in the same study, contributed 3% to health outcomes. Moreover, the influence of social relationships on the risk of death are comparable with well-established risk factors for mortality such as smoking and alcohol consumption, and exceed the influence of other risk factors such as physical inactivity and obesity.[2] For example, in neurology, poor social relationship has been associated with a 32% increased risk of stroke and a 50% increased risk of developing dementia.[3]

Why are these social factors so potent for health? How do we understand and potentially leverage them within clinical care for the neurology patient? Here, we offer answers by suggesting that the brain is a social organ biologically sensitive to social perturbations, and our psychological well-being is predicated on a social baseline. To understand and leverage such social determinants, we need to use established and new tools to measure social interactions across a range of modalities and design interventions that move beyond decontextualized biology to a contextualized psycho-social–biological approach.[4] We provide interdisciplinary theories and methods to achieve this goal.

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Definitions are useful at the outset. *Social networks* are the persons surrounding a patient who provide support, circulate information, and influence health behavior.[5] Social networks may be quantified using graph theory metrics so that their structure (e.g., size and density) and composition (e.g., proportion of family members vs. friends) are visually and statistically described.[6] *Social interactions* are the synchronous interactions between individuals through speech or computer-based communication (e.g., online interactions). The extent and nature of social interactions are the main constituents of social networks. *Social connection* is the structural (e.g., marital status, social networks), functional (e.g., perceived social support, feelings of loneliness), and qualitative (e.g., relationship satisfaction, friendship quality) aspects of social relationships.[7] *Social isolation* is the objective absence of social interactions, contacts, and relationships with family and friends, with neighbors on an individual level, and with "society at large" on a broader level.[8] *Loneliness* refers to the subjective perception of social isolation or the feeling of being lonely.[3]

In this article, we will begin with a review of the significance of social networks in terms of its biological and psychological necessity. This will include an introduction to the social brain followed by the psychology evidence linking social connection to well-being and physical health. We then identify the gap in translating the research of social networks into clinical practice. We propose that a new model is needed that is germane to clinicians. The social network paradigm is one model that reimagines neurology patients as embedded in quantifiable social networks. Finally, we suggest the next steps in the development and use of novel assessment tools that measure social life, and the design of social network interventions to improve health outcomes.

Biological Importance of Social Connection

The brain is a social organ in terms of its evolutionary development, anatomic prioritization for social cognition, and response to isolation. The human brain, at nearly four times the size of our closest evolutionary neighbors, possesses remarkable ability to make inferences about others and is unique in its capacity for language and civilization.[9] Given the centrality of sociality to our lives, some argue that the human brain has evolved to specifically perform complex social behaviors.[10] According to the social brain hypothesis, Robin Dunbar argued that the cognitive demands of social life have served as the dominant selective pressure for mammalian brain size.[11] Specifically, cortical thickness increases with species' group size, particularly in regions associated with social cognition such as frontal polar, insular, and temporal cortices.[12,13] Individual differences in social network size may also be associated with increased volume of brain areas involved with affective and executive function, including the amygdala and prefrontal cortex.[14,15] Some researchers have questioned whether this increase in brain size arises from a unique social component, or whether this difference may instead reflect cognitive demands of non-social tasks such as threat detection and foraging.[16,17] However, the dominant view is that a strong relationship exists between social life and brain development.

Development and Specialized Systems of the Social Brain

The social environment–brain development relationship (ecobiodevelopment) begins with a prolonged period of brain growth in humans. Humans need to be social learners because they are highly dependent in early life. Infants are unable to take their first steps until a year of age, feed themselves sufficiently until at least age 2, or navigate parts of the world for a decade. Yet, they can distinguish human faces from other stimuli by 1 week, associate lip movements with sounds by 5 months, and preferentially seek information from reliable social agents by 18 months.[18] Such early social learning is required for threat identification and survival. Brain growth is also delayed in humans compared with other species. Human infant brains are 25% of their adult size, compared with 50% in chimpanzees and nearly 70% in macaques.[19] The majority of growth in adolescence appears to occur in brain regions associated with social cognition and executive function.[20] Therefore, the luxury of delayed brain growth allows for the development of complex reasoning, communication, and social interaction.

This development fosters the emergence of specific brain regions (and interconnected networks) subserving social cognition, most notably mirror neurons discovered in the 1990s. Situated predominantly in the prefrontal cortex in macaques and humans, mirror neuron networks are active when an individual sees an action in another individual:

> Each time an individual sees an action done by another individual, neurons that represent that action are activated in the observer's premotor cortex. This automatically induced, motor representation of the observed action corresponds to that which is spontaneously generated during active action and whose outcome is known to the acting individual. Thus, the mirror system transforms visual information into knowledge.[21]

Mirror neurons converge visual actions with motor responses, creating a neurobiological basis for intersubjectivity.[22] Other areas associated with social cognition are the prefrontal cortex, nucleus accumbens, and amygdala, as demonstrated in functional neuroimaging studies.[23] For instance, inferring goals and intentions of others strongly recruits activity in the temporoparietal junction, whereas abstractions of traits and norms engage the medial prefrontal cortex.[24,25] Functional near-infrared spectroscopy studies suggest that interacting social partners, such as parent–child pairs, synchronize activity in limbic areas, and the temporoparietal junction.[26] Some regions appear to have specialized social functions, such as the fusiform gyrus for facial recognition. These regions appear to process higher-order social information with limited responsiveness to low-level auditory or visual features.[27] One study of fusiform gyrus topology followed a cohort of adults with experience playing Pokémon, a popular video game in the early 1990s featuring animal-like characters. Compared with novices, experienced players showed robust activation in lateral fusiform gyrus in response to viewing Pokémon characters, highlighting the neuroplastic

consequences of lived experiences.[28] Similar patterns have been observed in the prefrontal cortex, temporal, amygdala, and inferior parietal areas, where early linguistic exposure can shape preference for phonemes in speech.[15,29] These findings suggest that multiple brain regions (and related brain networks) are activated by social behaviors and are adept at incorporating new information throughout development.

Some models suggest that social cognition may not be limited to specialized brain regions but may instead arise from domain-general mechanisms.[30] The predictive coding theory, for instance, posits that the prefrontal cortex generates Bayesian estimates of prior sensory data and iteratively adapts to bottom-up "errors," or discrepancies between incoming and predicted sensory data. Thus, the prefrontal cortex is constantly evaluating new information against an internal model of the world. This idea is supported by hierarchical organization of error representations within the prefrontal cortex, where ventral areas respond to abstract information, caudal areas to incoming sensory data, and medial and dorsolateral areas to various degrees of sensory error.[31] Such organization can also be observed in the visual cortex, dopaminergic midbrain, and mirror neuron systems associated with social cognition.[32,33] These findings may explain why regions such as the temporoparietal junction are strongly engaged by both perspective-taking and prediction of movement trajectories—as social modules may be adept at developing Bayesian estimates of behaviors that inform both social and nonsocial cognition.[34] Generalized errors in prediction have also been used to explain broad-ranging motor and social deficits observed in individuals with autism spectrum disorder.[35] Collectively, these models suggest that higher-order representations of social information, such as human faces or language, may reflect predictions of sensory information aggregated over development.

Social Environmental Enrichment and Neuroplasticity

The brain's ability to adapt to a dynamic social environment involves plastic changes at the level of synapses, neural networks, and brain morphology. In the healthy adult brain, neurogenesis primarily occurs in the subgranular zone of the hippocampus, which gives rise to cells that receive input from limbic areas.[36] Neuroplasticity is locally upregulated in the setting of neurological injury. After stroke, for instance, regions surrounding infarcted tissue demonstrate increased neurogenesis, allowing for behavior-driven plasticity during recovery.[37,38] These changes are driven by several mechanisms, such as enhanced neuronal activity in peri-infarct tissue,[39] angiogenesis,[40] expression of growth factors,[41,42] and suppression of apoptosis.[43] Social stimulation has been shown to enhance these neuroplastic processes in normal and brain-damaged animals. This phenomenon was first studied by Donald Hebb, who observed that mice raised in his home showed superior problem-solving abilities compared with those raised in laboratory conditions. This rich home environment, which involves social, cognitive, and physical stimulation akin to that encountered in nature, has been termed *environmental enrichment*.[44] His work was followed by a series of experiments that showed that environmental enrichment can induce plasticity in the healthy adult brain as well as the injured brain.[45–47] The absence of social stimulation has also been associated with impaired plasticity and cognitive deficits, many of which can be potentially restored with resocialization.[48] The underlying mechanisms of social stimulation largely overlap with, and upregulate, neuroplastic processes that occur during recovery from neurological injury. These mechanisms are summarized in ►**Table 1**.

Collectively, these studies suggest that environmental enrichment paradigms may hold clinical utility in enhancing recovery after neurological injury. Environmental enrichment has been broadly defined as a stimulating environment which mimics natural conditions and includes housing configuration (multilevel cages, toys), cognitive stimulation (mazes, visual stimuli), social stimulation, and exercise. Preclinical studies of enriched environments have shown robust and consistent benefits in post-stroke animals for over 60 years.[49–51] Some studies suggest that environmental enrichment generates a permissive regenerative state that prolongs plasticity in recovering peri-infarct tissue.[51] Environmental enrichment with exercise has been shown to

Table 1 Mechanisms of environmental enrichment-induced neuroplasticity

Mechanism	Environmental enrichment-induced plasticity
Morphologic changes	↑ Dendritic remodeling[95] ↑ Axonal remodeling[96] ↑ Synaptogenesis[97]
Vascular changes	↑ Angiogenesis[40] ↓ BBB leakage[69,98]
Immune changes	↑ Antioxidant activity[99] ↓ White matter damage[69]
Neuronal growth	↑ Growth-promoting factors (BDNF, Gap43, FGF-2)[41,42] ↓ Growth-inhibiting factors (aggrecan-containing perineuronal nets, NOGO)[47,67] ↑ Antiapoptotic factors (BCL-2)[43] ↑ Neurogenesis[43,100]
Neuronal activity	↑ Activity in perilesional cortex[39] ↑ Excitatory neurotransmission[48]

enhance sensorimotor recovery,[38,47] upregulate growth factors in peri-infarct cortex,[51] and attenuate blood–brain barrier leakage following stroke.[52] While environmental enrichment paradigms vary in the degree of social, cognitive, and physical stimulation, they may be contrasted against rehabilitation settings where patients are often socially isolated and physically inactive.[53,54] Preliminary studies of patients with stroke show moderate benefits of environmental enrichment, including increased physical activity and cognitive improvement.[55–57] Questions remain about clinical translation—implementation will require a careful assessment of the feasibility of long-term environmental enrichment, the structure of enrichment paradigms, and the time window during which enrichment is most critical for recovery. Efforts to develop such a framework are currently underway and represent a promising new avenue in stroke recovery.[58,59]

Psychological Importance of Social Connection

For humans, their everyday social context and the connections they have with people around them constitute a key component of environmental enrichment. Humans are fundamentally a social species, and social interactions are both necessary for their survival and key to their thriving. This highly robust and replicable finding has consistently emerged over the last few decades of psychological research and has by now reached the status of a consensual scientific fact.[60–62] According to the *social baseline theory*, humans' default way of operating in a world of daily challenge and threat is an inherently social one, one in which the brain, as a baseline, assumes proximity to social resources and defaults to a social mode of coping. This is due to the phylogenetic adaptation based on an assumption that to be embedded in a social network offers opportunities for connection, belonging, and support.[63,64]

Consequently, when humans are integrated into social communities and feel like they contribute to them in meaningful ways, their bodily systems tend to function in biologically adaptive ways, facilitating long-term mental and physical health benefits. On the other hand, when their sense of belonging and social integration is chronically thwarted, biological processes become dysregulated, allostatic load accumulates, and bodily systems succumb to their wear and tear, leading to increased propensity for morbidity and early mortality.[65] The insight that social connection is instrumental to human health and well-being led the World Health Organization (WHO) to list "social support networks" as a determinant of health alongside factors such as income, education, social status, and access to health services.[66] And, consistent with that, there are now strong and repeated calls to advance social connection as a public health priority.[67]

Social Connection and Well-being: Evidence from Naturalistic Observation

Several studies have linked having more social interactions to higher well-being. In most studies, however, social interaction and well-being are both assessed via self-report surveys. Though a valid and efficient method for testing the association between social connection and well-being, the strongest evidence arguably comes from studies where the two variables are assessed with different methods. Measuring a predictor and outcome with the same method can spuriously inflate effects when response biases affect the predictor and outcome measure in parallel ways (e.g., demand characteristics, socially desirable responding).[68]

Investigators have aimed at minimizing this concern by assessing social interactions objectively and in ecologically valid ways without relying on participants' perceptions and memory. Specifically, one method is the Electronically Activated Recorder (EAR).[69] Technically, the EAR is an audio recorder (originally an analog microcassette recorder, currently a smartphone app) that intermittently records brief snippets of ambient sounds while participants go about their lives. Conceptually, it is a naturalistic observation method that yields an acoustic log of a person's day as it unfolds. The sampled ambient sounds are then coded for participants' moment-to-moment social contexts (e.g., at home, outside), activities (e.g., watching TV, eating), and interactions (e.g., alone, talking with others). The EAR method has been successfully used in age groups ranging from childhood to old age and with both healthy and clinical populations, and a series of safeguards is put in place to protect the privacy and confidentiality of participants and their conversation partners.[70]

In one study, Dr. Mehl and colleagues aimed at providing a first estimate of the association between objective social interaction quality and quantity, as assessed with the EAR, and well-being.[71] Seventy-nine college students wore the EAR for 4 days. The amount of time participants spent alone and the amount of time they spent talking with others were extracted as markers of the quantity of students' daily conversations. The amount of small talk (defined as an uninvolved, banal conversation where only trivial information was exchanged) and the amount of substantive conversations (defined as an involved conversation where meaningful information was exchanged) were extracted as markers of the quality of students' daily conversations. Across different measures of well-being (self-reported life satisfaction, self-reported happiness, and friend-reported happiness), spending less time alone and more time interacting with others (i.e., higher interaction quantity), and having less small talk and more substantive conversations (i.e., higher interaction quality) were related to higher well-being.

Recognizing the small sample size and homogeneous population, Milek and colleagues recently aimed at replicating this finding.[72] Using data from four EAR studies with a combined sample size of almost 500 participants, they confirmed that spending less time alone and more time interacting with others (i.e., higher interaction quantity) and having more substantive conversations (i.e., higher interaction quality) was again reliably related to higher well-being. To illustrate the magnitude of the effect, the happiest and the unhappiest participants in the sample differed by an estimated amount of 4 hours of daily social interactions. Interestingly, the original negative small talk

effect failed to replicate, suggesting that it may have been a false-positive finding. Small talk might not be a good marker of low interaction quality due to its role in routine social scripts. Also, with its large sample size, this study could test the extent to which personality mattered for this effect. Interestingly, no significant moderation effect emerged, suggesting that, counter to lay intuition, having many daily interactions was not more closely linked to well-being for extraverts, and having quality (rather than superficial) interactions was not a stronger predictor of well-being for introverts, pointing to overall comparable "well-being returns on social interaction investment." These studies provide evidence that individuals who have more and more meaningful social interactions experience higher well-being. However, with their cross-sectional design, they cannot speak to directionality and causality, or whether individuals are happier in moments when they have more meaningful interactions.

This complementary question was recently explored by Sun et al using the same methodology.[73] In their study, 256 participants wore the EAR for 1 week and provided momentary reports of happiness and social connection. Interaction quantity (i.e., talking with someone) emerged as robustly associated with greater well-being in the moment. Interaction quality (i.e., conversational depth) was also generally associated with greater momentary well-being, but the effects were less consistent than for interaction quantity. With respect to the role of personality, this study also found that most effects were comparable for introverts and extraverts, although extraverts, compared with introverts, experienced greater social connection when engaging in deeper conversations. Taken together, these studies converge with findings from other self-report–based studies that there is a clear and robust positive link between social connection and psychological well-being.

Social Connection and Physical Health: Evidence from Meta-analyses

In addition to being associated with better psychological well-being, social connection is also linked to better physical health including longevity. Several meta-analyses have now robustly documented this effect, such as a meta-analysis of the effects of social relationships on mortality,[2] a meta-analysis of the effects of divorce on mortality,[74] and a meta-analysis of the effects of marital satisfaction on health.[75]

To better characterize these effects, we review the findings from the most recent and most comprehensive meta-analysis in detail.[76] In this study, Holt-Lunstad and colleagues estimated the effects on mortality of (1) social isolation (i.e., a lack of social contact/communication), (2) living alone (vs. living with others), and (3) loneliness (feelings of isolation/not belonging). Across the 70 studies reviewed (>3 million included participants), the overall effect size was: odds ratio (OR) = 1.53 (95% confidence interval [CI]: 1.38, 1.70) with the three measures showing statistically comparable effect sizes (social isolation: OR = 1.83; living alone: OR = 1.51; loneliness: OR = 1.49). This OR can be interpreted that participants who lacked social connection, objectively or subjectively, had 50% higher odds of dying over the course of the follow-up (on average, 7 years). Further models that accounted for covariates (e.g., initial health status, gender, age, and socioeconomic status) yielded somewhat smaller yet still substantial effect sizes. The fully adjusted overall effect size was: OR = 1.30, 95% CI [1.16, 1.40] (social isolation: OR = 1.29; living alone: OR = 1.32; loneliness: OR = 1.26), reflecting 30% increased odds of dying during follow-up for socially isolated participants. Importantly, the prospective nature of the studies included in this meta-analysis, the statistical models that controlled for initial health status, and the fact that the effects were retained when controlling for sociodemographic factors with known links to health (1) provide evidence for the directionality of the effect and (2) suggest that social connection can impact health above and beyond the effects of other, more traditional determinants of health. Although this meta-analysis cannot unambiguously establish causality, "the data show that individuals who were socially isolated, lonely, or living alone at study initiation were more likely to be deceased at the follow-up, regardless of participants' age or socioeconomic status, length of the follow-up, and type of covariates accounted for."[76]

When benchmarking the findings from this and the other meta-analyses against the established effects of leading health risk and protective factors, the effect sizes for social connection (and social isolation, inversely) are on par with and in some instances exceed the effects of air pollution, obesity, physical activity, excessive alcohol consumption (> 6 drinks/day), and smoking (> 15 cigarettes per day).[77] This fact has led to the intriguing yet, at the same time, almost obvious idea that patient care can benefit from expanding the traditional set of vital signs that are routinely collected as part of health care visits (e.g., weight, blood pressure, physical activity, alcohol use, tobacco use) to include a set of psychosocial vital signs with demonstrated relevance to health.[78,79] Notably, one of the four proposed psychosocial vital signs is social connection versus isolation. At the moment, it is proposed to be measured via self-report using four items from the Berkman-Syme Social Network Index ("In a typical week, how many times do you talk on the telephone with family, friends, or neighbors?" "How often do you get together with friends or relatives?" "How often do you attend church or religious services?" "How often do you attend meetings of the clubs or organizations you belong to?").[80] It is easy to imagine that, in the future, information about patients' social connection will not be collected via their self-report, but rather will enter their electronic health record via an upload of pertinent digital behavioral markers from smartphones and wearables.[81]

The Gap in Translation to Clinical Neurosciences

The major gap in the research area of social connection and medicine (including neurology) is a lack of translation to interventions. As discussed in the National Academies of

Science, Engineering, and Medicine consensus report on social isolation and loneliness in older adults,[3] we will review the challenges that contribute to this gap.

There is no universally accepted and comprehensive measurement system for social connection. As a multifactorial risk factor, a complete assessment would include objective and subjective data, structural and functional data, and in-person and online data. Incorporation of this multidimensionality would enhance predictive value.[4] Clinical cutoff scores and risk classification systems would also be helpful to identify patients at risk.

There are underrepresented populations in current studies. Particularly, in neurology, patients with cognitive or communication deficits who cannot self-report are not captured in most studies. Caregiver proxy validation is underdeveloped in this area. Other underrepresented populations include younger persons, ethnic minorities, persons from low- and middle-income countries, and those with disabilities.

Social media has become a dominant form of social interaction in recent years, but there are few academic measurement tools that capture these data. This is partly due to privacy restrictions by large social media companies that reasonably constrain access. But also, more attention is needed to conceptually reconcile online versus in-person interactions as it pertains to constructs such as social support (and their relative positive and potentially negative consequences).

Finally, social intervention implementation is challenging. In clinical studies, the definition of a social network member/caregiver to target is the initial step that often requires social network mapping. Then, the multiple persons around an index patient need to be approached, consented, and engaged. Moreover, the key drivers of social influence that occur naturalistically require creative thinking to experimentally modify or enhance. For example, enhancing cooperative behavior, support, or communication in groups is not routine in clinical medicine, although successful examples exist in addiction medicine.[82,83] Finally, scaling interventions require a thoughtful implementation and dissemination process examining gatekeepers and stakeholders, opinion leaders and change champions, and educational outreach.

Social Network Paradigm for Clinical Neurology

In 350 BCE, Aristotle stated, "Man is by nature a political animal [*zoon politikon*]."[84] He argued that a flourishing human must *not* be considered as a single individual living a solitary life, but as a person with parents, children, wife, friends, and countrymen. In medicine, we have not heeded this advice. The patient in the clinic or research context is treated as a solitary figure. Social network theory aims to reorient this perspective. The theory proposes that every person is embedded in a social network of interpersonal connections that can influence health through, for instance, diet, exercise, and other lifestyle habits. Social networks are channels of influence through which information, social support, and behavioral cues flow from interpersonal contacts. In fact, there is a deep interdependence of social actors, and any individual action is embedded in, and therefore continually affected by, preexisting ties built on trust and reciprocity. Therefore, measuring and leveraging social networks may be a strategy for some of the most difficult medical ailments. Indeed, ignoring them may be a key reason that behavioral interventions fail.

Given this philosophical basis, Dr. Dhand and colleagues developed the theory that neurology patients are best understood in the context of their social connection (►**Fig. 1**). To operationalize the theory, the group developed PERSNET, a quantitative social network assessment tool on a secure open-source web platform, readily deployable in large-scale clinical studies. Using PERSNET, participants generate names of social network members, their inter-relations, and each member's demographic and health characteristics. A set of statistics on the graph and visualization are produced (►**Fig. 1**). The conceptual groundwork and methods allowed us to study the social networks of patients with varying neurological conditions including stroke,[5] traumatic brain injury,[85] and multiple sclerosis.[86] International research groups have also used PERSNET to study varying public health phenomena such as the social network drivers of indoor air pollution.[87] Our empirical studies have revealed significant and counterintuitive results. For example, we found that small and close-knit social networks of highly familiar contacts, independent of individual characteristics, were related to *delayed* hospital arrival after stroke.[88] This was because the closed network structure led to constricted information flow in which patients and close confidents, absent outside perspectives, decided to watch-and-wait. In stroke recovery, we found that even though social networks became smaller and close-knit, they also became healthier. Larger baseline social networks were independently associated with better patient-reported physical function after stroke.[5]

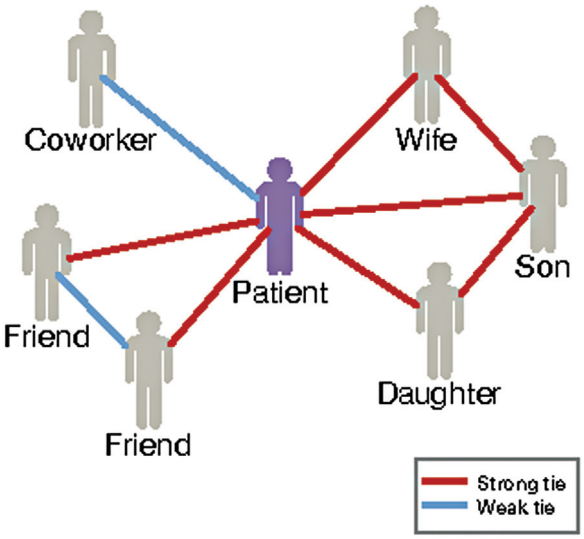

Fig. 1 Illustration of the personal network of a patient.

Novel Assessment of Social Connection in Clinical Contexts

Moving from conceptual framework to clinical intervention requires further methods for assessing social connection. The study of social connection has mostly been in community samples, particularly in older adults with an epidemiological design. The traditional instrument is a survey. Given the multidimensional nature of the construct, investigators have developed instruments probing different aspects of social connection (►**Fig. 2**). Two of the most useful in the clinical setting are the Berkman-Syme Social Network Index and the UCLA loneliness scale. In a head-to-head comparison between PERSNET and the Lubben Social Network Scale–Revised and Stroke Social Network Scale in a clinical context, we found that PERSNET had similar psychometric properties to these core measures while allowing for social network visualization.[6]

However, there are clear limitations to retrospective self-reports, particularly in clinical contexts. For example, we have found that 45% of patients who have a stroke cannot complete questionnaires during hospitalization due to cognitive or language deficits. Therefore, passive naturalistic observation sampling, a type of experience sampling, has emerged as a method to measure psychosocial factors in daily life. Naturalistic (or ecological) observation sampling methods use social sensors (e.g., audio, picture, video) that may be used in patients with varying deficits. We summarize some of the leading technologies in this area in ►**Table 2** with commentary below.

Electronically Activated Recorder

The EAR is an ambulatory ecological momentary assessment tool for the real-world observation of daily behavior. Technically, it is a smartphone app that silently records brief (e.g., 30 seconds) snippets of ambient audio intermittently (e.g., five times per hour) throughout the day. This approach provides a distributed acoustic log of the user's day. The raw audio is stored on the device where the user can manually review and remove any recordings that may compromise their privacy. To obtain descriptive features from the recordings, researchers must manually review and transcribe each recording, a demanding task. Challenges of the EAR method revolve around the privacy protection of conversation partners and bystanders that might be captured on the raw ambient audio recordings.[69]

Tracking Individual Performance Using Sensors (TILES)

The TILES audio recorder aims to make experimental audio collection more efficient and secure. In previous approaches, audio was recorded at fixed intervals and stored on the device until its eventual analysis and deletion. It is impractical for these types of approaches to accurately measure all audio activity given that the likelihood of a random audio event occurring at the same time as the recording interval is low for all audio events. The TILES recorder remedies this issue by constantly sampling the microphone and extracting computationally cheap, low-level, spectral energy features. If these energy levels exceed a certain threshold, audio is recorded for a set period. TILES yields significant value

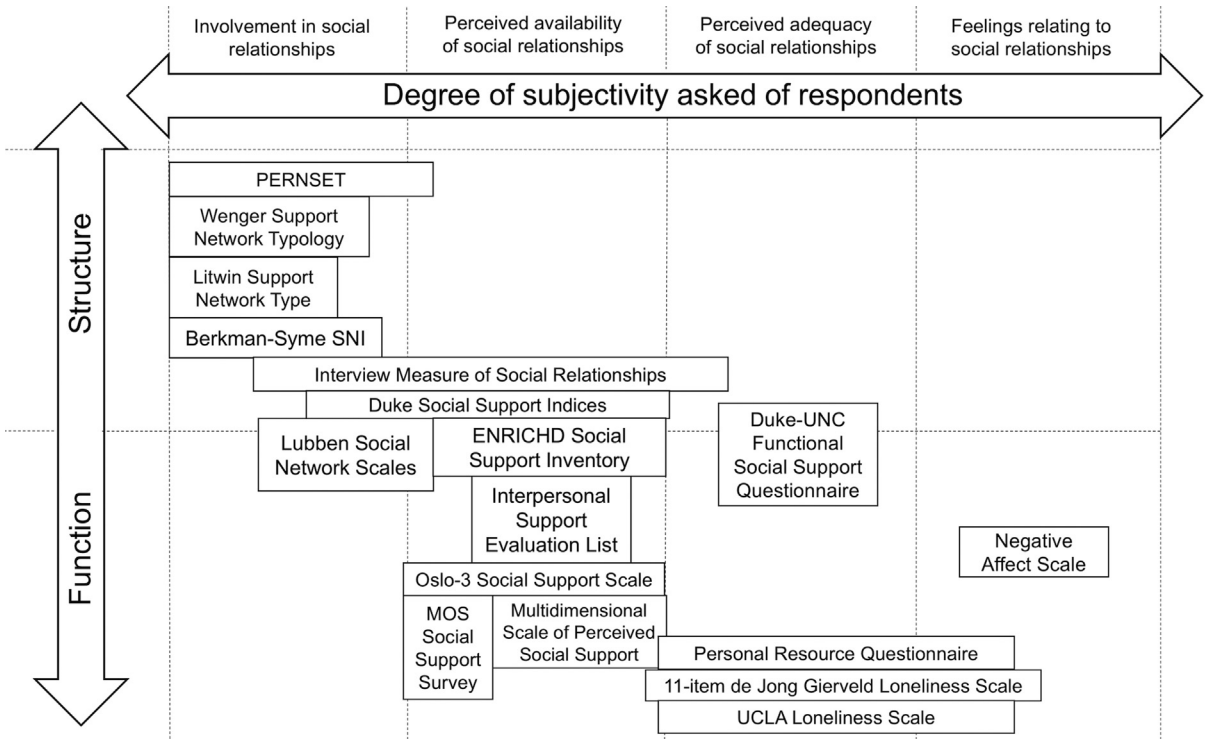

Fig. 2 Social network survey instruments organized by structure versus function and degree of subjectivity. (Source: Adapted from Valtorta et al.[104]).

Table 2 Examples of tools that can be used to assess social connections in a clinical context

Device	Type	Method	Approach	Optimized for assessment of	Advantages	Disadvantages
EAR: The electronically activated recorder	Ambulatory ecological momentary sampling tool	iOS/Android app Behavioral observations (raw audio data)	Records brief (e.g., 30 s) snippets of ambient audio intermittently (e.g., five times per hour) throughout the day. It is worn by participants as they go about their lives. The naturalistic observation sampling results in an acoustic log (i.e., ambient sounds) of a person's day.	Observable social interactions	High measurement flexibility. Psychometric properties documented. Holds raw audio for multiple days with good battery efficiency.	Privacy intrusion. High coding burden for researcher. Moderate temporal resolution.
TILES: an unobtrusive wearable solution for tracking audio activity	Mobile phone app, data collection tool	Android app Capture audio data only when necessary	Run silently in the background of user's phone. Continuously sample the microphone, begin recording if an audio event is detected. Store audio features rather than raw audio.	Efficiently collecting relevant audio data	Long battery life. Nonintrusive to the user's everyday life. Reduces amount of useless data being collected. Maintains user privacy.	Abrupt audio events may never be recorded due to the mechanics of the recording mechanism. Researchers must manually tune parameters.
Sociometric badge: a wearable device to measure team collaboration	Wearable electronic badge for behavior analysis	Standalone device Monitor social activity through microphone, accelerometer, and infrared sensor data	Worn around the neck of participants as they go about their work day. Audio features are collected in real time and stored on the device. Offline analysis is performed on the stored features to infer social patterns.	Capturing fine-scale speech and activity patterns among a group of individuals	Designed for inter-team behavior analysis. Robust to a variety of social activities. Long battery life. Maintains user privacy.	High cost per device. Standalone device Involved setup process for researchers. Device is not appropriate for measuring interaction in casual social settings.
BeWell: a smartphone app to monitor and promote well-being	Behavioral tracking for improved well-being	Android app Monitor social activity through microphone, accelerometer, and GPS sensors	Samples sensors in real time and performs classification on device. Monitors behaviors that are impactful on an individual's well-being. Users are recommended behavioral changes to promote better health.	Tracking social activities that are critical to user's well-being, namely, sleep, physical activity, and social interaction	Accessible and affordable. Robust to a variety of social activities. Non-intrusive to the user's everyday life. Low impact on battery.	Classification is performed on device, leading to poor battery life. Prone to errors from ambient sound (TV, radio, etc.).
SocialBit: a smartwatch app for measuring social interaction	Tracking of social interaction	Smartwatch app (wear OS) Monitoring social interaction through the microphone	Smartwatch app that quietly runs in the background as users go about their lives. 1 min of audio recorded once every 5 min. Utterance recorded by user to classify their speech.	Audio-based observation of social interactions	Robust to a variety of social settings. Nonintrusive to the user's everyday life. Maintains user privacy. Ability to personalize algorithm (via user utterance).	Battery intensive Only tested on a small dataset. Prone to errors from ambient sound (TV, radio, etc.).

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from the data it produces at a computational cost much lower than previous approaches.[89]

Sociometric Badges

Sociometric badges are designed to measure and understand inter-team collaboration patterns. The device is small and is worn on a lanyard by each member within a team. The device records data in real time using a variety of built-in sensors, namely, an infrared emitter, accelerometer, and microphone. Investigators extract data to classify periods of face-to-face interaction, physical activity, and conversation. These data are useful to assess inter-team collaboration in different work-related scenarios. However, the badge is not fit to measure everyday casual interactions due to the fact that all participants must have their own badge.[90]

BeWell

BeWell is an app to monitor and promote well-being.[91] The app runs silently on the user's phone and samples the microphone, accelerometer, and GPS in real time. The app classifies data within the health behavior domains of physical activity, social interaction, and sleep patterns. The aim is to quantify and improve well-being. Challenges for social interaction inference include ambient sound around the participant (such as television or side conversations). The conversation detection algorithm developed originally within the BeWell app has also been integrated into the StudentLife app, a mobile sensing application that is currently widely used in the field of psychology and computer science.[81,92,93]

SocialBit

SocialBit is an algorithm developed in a clinical context with neurology patients. SocialBit works on various wearables to detect social interactions while maintaining users' privacy. The algorithm recognizes social interactions based on the temporal change of sound and vocal acoustic behavior characteristics such as pitch and intensity. It then classifies the data as one of two classes: social interaction or not social interaction. The result is quantification of the number of social interaction minutes per day. Importantly, investigators are training the algorithm on patients with diverse cognitive and communication deficits including aphasia, abulia, and delirium. The resultant algorithm will therefore be useful for neuro-typical and neuro-atypical populations.

Designing Social Network Interventions for Neurological Patients

Network interventions are the process of using social network data to accelerate behavior change or improve group performance.[94] Network interventions are a type of social intervention, which include varied strategies described in ►**Table 3**.[3] In a clinical sense, a network intervention is the translation of the scientific study of social networks in patients into an effective and sustainable treatment approach. Ultimately, the goal would be a scientifically validated method and practice to leverage social networks to improve patient outcomes. There is a precedent for this strategy in other fields.

In alcohol use disorder, a randomized control trial of "Network Support Treatment" that aimed to enhance the ability of patients to construct abstinence-supportive social networks was compared against a cognitive behavioral therapy control treatment. Investigators found that Network Support led to more days of abstinence.[83] In hypertension, investigators evaluated the effect of education administered within social networks on improvement of hypertension compared with historical controls. They found that at 18 months, the intervention group had a significantly larger drop in systolic blood pressure (-4.82 mm Hg, $p < 0.001$) and diastolic blood pressure (-3.37 mm Hg, $p = 0.01$) compared with controls.

However, these results are tempered by negative trials for social support interventions in stroke. For example, the FIRST study, a multicenter randomized control trial of a family-system intervention to influence social support and self-efficacy showed no benefit in functional recovery at 6 months after stroke. Researchers have suggested that these failures are due to a lack of consensus on definitions of "informal caregiver" or social unit targeted in studies, unknown ideal timing, duration, and intensity of intervention, and coarse outcome metrics (e.g., disability scales instead of patient-reported outcomes).

To design a network intervention, one must address (1) who to target and (2) what change to provoke in the network structure and/or function. For targeting, interventionalists may produce a network map for the index patient (e.g., ►**Fig. 1**) to identify the set of persons who may be approached. The detail of the network mapping need not be at the same level as research purposes, as a low-resolution map could suffice to identify the key players. Once a map is produced, the network data can help identify certain individuals to target. However, the decision about whom to target still requires careful thought—do we want the most central actors, the positive influencers, the ones who have the same risk factor that we're trying to alter in the patient, or those who are most accessible?

Next, interventionalists need to determine what change they want to provoke in network structure and/or function. Structurally, Valente's network intervention typology suggests four relevant types of change[94]: *individual*—using network data to target certain individuals (e.g., opinion leaders); *segmentation*—targeting groups of people clustered in a network (e.g., team-based goal acquisition); *induction*—stimulating peer-to-peer interaction to create information diffusion (e.g., word of mouth); *alteration*—changing the structure of the network by the addition of new members or reduced time with negative influencers (e.g., alcoholics anonymous; ►**Fig. 3**). Functionally, networks are conduits of support, information, and behavior cues. Interventionalists need to think about what they want the network to do to reach the desired outcome and how this is going to be learned and sustained. For example, if support is the main ingredient for improving recovery, then interventionalists could consider helping the group define a set of support

Table 3 Social intervention types and examples relevant to a clinical context

Types	Examples
Social prescribing	Connecting people with volunteer organizations and community groups
Support groups and group membership	Peer support groups; SilverSneaker fitness program for older adults[101]
Skill-based psychotherapy	Cognitive behavioral therapy; interpersonal therapy; mindfulness
Pharmaceuticals	Selective serotonin reuptake inhibitors, neurosteroids for loneliness and its associated anxiety and fear
Interventions targeting social determinants of health more broadly	Community-based intervention to increase stroke preparedness through peer-led education[102]
Interventions targeting social isolation and loneliness in a health care system	Togetherness program in CareMore Health involving Phone Pal, home-based visiting program, care centers as social hubs[103]
Interventions targeting specific risk factors	Treating hearing loss with hearing aids
Technology	Promoting internet use; promoting social media use; social robots, and conversational agents
Network interventions	Leveraging social network support for abstinence maintenance[102]

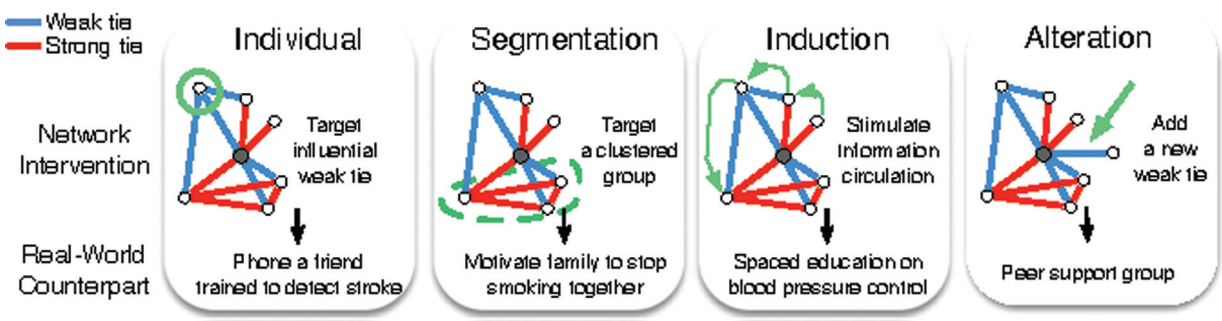

Fig. 3 Network intervention types and real-world counterpart examples.

tasks, assign responsibilities and accountability, and set rewards for achieving goals. An example of the planning and randomized testing of successful intervention is the Network Support treatment mentioned earlier.[83]

In today's neurology practice, we offer one example of the design of a social network intervention to control hypertension after ischemic stroke currently under investigation. Achieving adequate blood pressure control (<130/80) after stroke is challenging. Up to approximately 60% of patients have uncontrolled blood pressure at 1 year after stroke. Interventions to address blood pressure control in stroke survivors have ignored the social context forces on medication adherence and lifestyle choices. Acknowledging the influence of social networks to regulate medication adherence, diet, and physical activity, the study team hypothesized that leveraging a patient's social network to monitor and control blood pressure would be more effective than individual counseling. To test this hypothesis, the investigators designed a randomized control trial of 60 hospitalized stroke survivors to assess the effects of a social network intervention versus individual hypertension counseling on blood pressure control after ischemic stroke. The primary outcome was the absolute reduction in systolic blood pressure at 3 months.

In the *social network arm*, the patient's personal network was mapped. Informed by the network map, the study team identified highly connected network members and teams. The study team invited identified social network members into the trial. Patient and social network members met a clinical nurse on Zoom in weeks 2, 6, and 12 after stroke. For 30 minutes during each of the first two sessions, the clinical nurse facilitated a session on teamwork, roles and responsibilities, and development of a team-oriented plan for the patient to achieve the goal blood pressure. Specific jobs for network members included support for taking and adjusting medications, monitoring blood pressure, facilitating eating non-salty foods, and encouraging physical activity. In the *individual counseling arm*, the patient alone met the clinical nurse on Zoom in weeks 2, 6, and 12. In equalized exposure to the nurse, the 30-minute session was spent on medication adherence strategies, blood pressure monitoring, and diet and exercise. The third session for each group was dedicated to directly observing the final blood pressure measurement. Results are forthcoming. This approach illustrates the systematic targeting of social network as an actionable intermediate mechanism of blood pressure control after stroke.

Conclusion

Once we conceive a patient as more than his or her biology, a method and practice to assess and, thereby, manage a patient

becomes more nuanced and multilayered. Social networks, though imperfect, are one concrete way to quantify and visualize the human ecosystem of direct influence on the patient's health. If such a conception is deemed useful, it is logical to consider stepping into the social network to influence it toward positive effect. By harnessing the power of social networks on some of the problems in neurology, which usually involve psychosocial behavioral drivers, the possibility of improved outcomes and health-related quality of life can be realized for the neurology patient.

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Conflict of Interest
A.D., M.S., M.R.M, and S.N. declare a provisional patent related to SocialBit.

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