Longitudinal intergenerational hyperscanning reveals indices of relationship formation and loneliness

Ryssa Moffat[1], Guillaume Dumas[2,3], Emily S. Cross[1]

[1] Social Brain Sciences Lab, ETH Zurich, Switzerland
[2] CHU Sainte-Justine Azrieli Research Center, Department of Psychiatry, University of Montreal, Quebec, Canada
[3] Mila – Quebec Artificial Intelligence Institute, Quebec, Canada

*** Correspondence:**
Ryssa Moffat
rmoffat@ethz.ch

Emily Cross
ecross@ethz.ch

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Abstract
Loneliness is globally acknowledged as a severe and burgeoning health risk, fuelling interest in helping people of all ages form meaningful social connections. One promising approach consists of intergenerational social programs. While behavioural and qualitative evidence derived from such programs promise health and wellbeing benefits, the physiological consequences of repeated intergenerational encounters remain unknown. Insight into physiological changes will shed light on the mechanisms of social connection and inform program design choices. We charted changes in interpersonal neural synchrony (INS) in 31 intergenerational (older/younger adult) and 30 same generation (younger adult) dyads across a six-session art program. At each session, dyads completed self-report measures, drew together and alone, and had their cortical activation recorded with fNIRS. In both groups, INS was greater while dyads drew together than alone. Across sessions, intergenerational dyads' INS decreased and same generation dyads' INS increased. Further findings highlight the promise of INS as a biomarker for changes in loneliness and the development of social relationships.

1 Introduction

Experiences of loneliness can have serious negative consequences for physical and mental health. As a result, widespread efforts are being made to combat loneliness (WHO, 2021). According to meta-analyses of behavioural studies, community programs providing opportunities for repeated contact between generations can improve older adults' (65+ years) physical, social, and cognitive health (Petersen, 2023), while also reducing younger adults' stereotypes about aging (Bartlett et al., 2021; Gonzales et al., 2010). Moreover, physicians are increasingly prescribing attendance at such programs–a practice called social prescribing (Scarpetti et al., 2024)–further highlighting the value the medical field attributes to such programs. To date the existing evidence base for intergenerational community programs consists of behavioural and qualitative studies. While offering promising results in terms of self-reported benefits and social engagement, such studies offer little insight into how or why intergenerational relationships develop on a physiological level. In this study, we sought

to provide a physiological perspective on the trajectory of intergenerational relationship development using a longitudinal hyperscanning approach, comparing intergenerational and same generation dyads who completed a six-week art program. Specifically, we tracked the trajectories of dyads' social wellbeing, abilities to collaborate, and levels of interpersonal neural synchrony (INS).

The following sections briefly describe the benefits of intergenerational social interactions, what is known about INS in intergenerational interactions, and the benefits of longitudinal perspectives on INS. Following this, we detail the aims and hypotheses of the present study.

1.1 Intergenerational social interactions to combat loneliness

Loneliness can be defined as "a negative, subjective emotional state resulting from a discrepancy between one's desired and actual experiences of connection" (WHO, 2025). Put more succinctly, loneliness can be thought of as *perceived* social isolation. Policy makers and researchers have long emphasised the severe risk that loneliness poses to physical and mental health (House et al., 1988; F. Wang et al., 2023; WHO, 2021). Public figures and media outlets go so far as to compare the adverse health impacts (e.g., mortality) of loneliness to those of smoking cigarettes (The Lancet, 2023). Considering everyday functioning, longitudinal studies show that loneliness and social isolation can precipitate declines in cognitive functioning including verbal ability, numeracy, and short-term memory (Ayalon et al., 2016; Cachón-Alonso et al., 2023). Loneliness is also associated with reduced perceptual speed (Drewelies et al., 2022) and biases toward negative evaluations of social information (J. T. Cacioppo & Hawkley, 2009; Okruszek et al., 2021; Spithoven et al., 2017). At the brain level, chronic loneliness and episodes of social isolation have been associated with altered structure (typically reduction in tissue volume) and altered function of prefrontal and posterior superior temporal cortices, as well as the insula, hippocampus, and amygdala (S. Cacioppo et al., 2014; Düzel et al., 2019; Lam et al., 2021). Attentional, visual, and default mode networks are also reported to show stronger functional connectivity in lonely individuals, which is believed to be associated with the bias toward processing social information negatively and a tendency toward increased rumination (Brilliant et al., 2022; Lam et al., 2021; Lieberz et al., 2021).

To combat loneliness, policy makers, researchers (Holt-Lunstad & Perissinotto, 2023; WHO, 2021; Wigfield et al., 2022), and health practitioners (Scarpetti et al., 2024) promote the creation of opportunities for meaningful social interactions for all members of society, and especially for those from populations most susceptible to loneliness. This typically involves initiating community programs that provide a platform for regular socialising opportunities (Bessaha et al., 2020; Noone & Yang, 2022; O'Rourke et al., 2018; WHO, 2025). Some community programs are intentionally designed to bring together members of different age groups, i.e., to be intergenerational. One reason for this is that people of all ages experience loneliness (Cigna US, 2018; Hawkley et al., 2022; Qualter et al., 2015). Another is that intergenerational social interactions can improve social and physical wellbeing for older adults, as well as increase empathy and feelings of social closeness toward older adults from younger participants (Petersen, 2023). The observed improvements seem to stem from repeated intergenerational contact (Lee et al., 2020; Lokon et al., 2020; Newman et al., 2014). In this context, repeated intergenerational contact requires regular engagement in intergenerational community programs, which is most likely to be achieved by ensuring that programs offer meaningful social interactions. One approach that has been shown to be particularly successful in this domain is arts-based and creative activities (WHO, 2019). Indeed, a growing body of evidence documents the social and physical health benefits of intergenerational arts programs for participants of all ages (Anderson et al., 2017; Jenkins et al., 2021; Lokon et al., 2020; Rubin et al., 2015).

Despite the mounting behavioural and qualitative evidence that repeated intergenerational interactions yield social benefits, including reduced loneliness, little is known about the physiological aspects that contribute to *how* and *why* these intergenerational programs offer such benefits. This is important because the physiological signatures of budding intergenerational relationships have the potential to be harnessed as tools to mitigate loneliness, yet they remain unknown (Moffat et al., 2024).

1.2 Interpersonal neural synchrony (INS) during collaborative intergenerational interactions

One source of physiological information is brain activity. Recording brain activity from two or more people while they interact is commonly referred to as 'hyperscanning' and offers a measure of interpersonal neural synchrony (INS; the extent to which patterns of brain activity are temporally aligned). Mobile functional near-infrared spectroscopy (fNIRS) and electroencephalography (EEG) are particularly well suited to recording brain activity during social interactions in real-world settings (Liu et al., 2018; Moffat et al., 2024). Hyperscanning with non-mobile techniques, such as functional magnetic resonance imaging (fMRI) and magneto-encephalography (MEG), is possible, though it offers less realistic social interactions and is less logistically feasible (Hirata et al., 2014; Misaki et al., 2021).

1.2.1 INS in social brain networks differs between solo and dyadic tasks

In studies comparing INS while dyads perform tasks collaboratively and alone, INS is consistently greater for collaborative performance than solo performance. This pattern has been observed for finger tapping (Holper et al., 2012), cognitive tasks such as n-back and object detection tasks (Cui et al., 2012; Dommer et al., 2012), singing (Osaka et al., 2015), tracing shapes on a screen using computer buttons or a stylus (Li et al., 2020; Sun et al., 2021), drawing specific verbs as in Pictionary (Xie et al., 2020), among other activities. A meta-analysis of fNIRS hyperscanning studies by Czeszumski et al. (2022) reports that during collaboration, INS is commonly observed between both interactants' prefrontal cortex (PFC), inferior frontal cortex (IFG) or temporoparietal junction (TPJ). INS in the prefrontal and inferior frontal cortices is proposed to reflect initiation and reception of joint attention (Koechlin et al., 2003; Redcay et al., 2012; Yoshioka et al., 2021), a social competence that depends on cognitive control (Ding et al., 2023; Mundy, 2018). INS in the TPJ, a key node of the Theory of Mind (ToM) network (Jacoby et al., 2016; Saxe & Kanwisher, 2003), is believed to reflect perspective taking and integration of social information (Czeszumski et al., 2022). Complementary findings from hyperscanning studies using EEG suggest that the strength and nature of collaboration shape the levels of INS recorded over frontal and prefrontal brain regions for alpha, beta, and theta frequency bands (Dikker et al., 2017; Dumas et al., 2010; Labonté-LeMoyne et al., 2016; Sinha et al., 2016; Toppi et al., 2016). In the context of INS in EEG signals, the alpha band may index joint attention and visual processing, while beta and theta bands may reflect joint encoding of sensorimotor information (Dikker et al., 2017; Dumas et al., 2010; Liu et al., 2018). In combination, the findings from fNIRS and EEG hyperscanning studies indicate that INS levels during collaboration are shaped by processes such as joint attention and perspective taking.

Many hyperscanning studies on collaboration can be considered intergenerational, in that they examine collaboration between parent-child/infant or student-teacher dyads (for reviews, see: De Felice et al., 2023; Nguyen et al., 2020). Though these studies offer the field of social neuroscience a valuable starting point for understanding intergenerational collaboration, two gaps in the literature have yet to be filled: First, the hyperscanning literature on collaboration distinctly lacks any representation of older adults. Second, the hyperscanning literature more generally offers very few

longitudinal perspectives into INS exceeding two time points. We now briefly explore the importance of addressing these gaps.

1.2.2 Older adults are underrepresented in hyperscanning research

To date, older adults' representation in the hyperscanning literature is limited to one hyperscanning study (Zhang et al., 2023), one study simulating INS (Dikker et al., 2024), and one position piece arguing for the inclusion of older adults in such studies (Moffat et al., 2024). It is critical to address this knowledge gap as the real-world settings in which older adults interact with younger adults and children (with their children and grandchildren, in assisted living, when seeking medical care, in community programs or through volunteer work) are numerous. Moreover, the proportion of older adults in the world's population is projected to continue growing until the end of this century. With an estimated 25% of populations across a number of global regions, including Europe and North America, expected to be older than 65 years in 2050 (United Nations, 2024), filling this knowledge gap will benefit a steadily increasing number of people.

In the one study to date exploring intergenerational INS involving older adults, Dikker et al. (2024) employed a neurocognitive model to simulate EEG-based INS during intergenerational social interactions between grandparents, parents, and grandchildren. In this seminal study, the authors found greater simulated INS between grandparent-grandchild dyads and grandparent-parent-child triads, relative to grandparent-parent and parent-child dyads. The authors report that the increase in simulated grandparent-child INS may be driven by age-related changes in the spectrum of brain activity. The authors also encourage the collection of real-world data to validate these simulations (Dikker et al., 2024). These findings underscore how including people of all ages, particularly underrepresented older adults, in intergenerational hyperscanning will enhance our understanding of INS across a broader range of everyday social interactions across the lifespan.

1.2.3 INS trajectories across days, weeks, and years remain uncharted

Most hyperscanning studies offer snapshots of INS in a single moment in time, and compare INS between contexts, tasks, or mental states. The *trajectory* in INS over days or weeks remains unknown, despite the value of granularity insights for understanding changes in behaviour related to the investigated contexts, task, and mental states. Longitudinal hyperscanning studies typically include two time points, as opposed to a denser sampling of the trajectory of INS. Numerous reviews from different domains of social neuroscience (e.g., developmental, clinical, communication etc.) recognise the lack of longitudinal insights into INS and call for longitudinal hyperscanning studies to be conducted (e.g., Adel et al., 2025; Bi et al., 2023; De Felice et al., 2025; Hoehl et al., 2025; Kelsen et al., 2022; Noreika et al., 2020; Turk et al., 2022). The discrepancy between the number of calls for studies tracking INS trajectories and the paucity of studies reporting them substantiates the critical need for additional multi-session hyperscanning studies. Concretely, multi-session longitudinal designs can fill in the blanks in our understanding of INS dynamics. A more fine-grained understanding of how the shared neural mechanisms underpinning social interactions change over time may help health practitioners maximize the social or cognitive outcomes of interventions (e.g., improving intergenerational communication, mitigating experiences of loneliness, identifying social difficulties, and general validation of interventions).

To the best of our knowledge, five hyperscanning studies have recorded INS at multiple sessions and subsequently analysed the aggregated time points, as opposed to reporting changes in INS across sessions (Bevilacqua et al., 2019; Dikker et al., 2017; Ellingsen et al., 2023; Grahl et al., 2021, 2023).

These studies are reviewed in greater detail in a position piece by Moffat et al. (2024). Only one fNIRS hyperscanning study offers insights into the trajectory of INS during relationship formation (Sened et al., 2025). Sened et al.'s (2025) proof-of-concept study tracked the trajectory of INS over bilateral IFG in 8 clinician-patient dyads at the first, third and fifth sessions of a 6-session intervention, where dyads completed imagery and cognitive behavioural training procedures. Sened et al. report increasing INS across sessions, as well as an association between increasing INS and reduced anxiety symptoms, improved wellbeing and perceived quality of session, but not the therapeutic alliance (i.e., the patient's rating of quality of the collaborative relationship between clinician and patient). One further study takes a unique approach to understanding INS in the context of relationship formation, though only encompassing two time points (D. Wang et al., 2024). INS was recorded from 11 dyads at two sessions, the first within 5 days of the dyad becoming flatmates, and the second after 7 months of co-living. Wang et al. report that social closeness can be predicted from INS with approximately 69% accuracy, using a deep neural network model and EEG hyperscanning recordings from frontotemporal brain regions. These two studies (Sened et al., 2025; D. Wang et al., 2024) provide preliminary evidence that INS between dyads increases as dyads grow more familiar with each other, however a larger sample size and number of time points would provide a richer picture of INS trajectories in developing relationships.

1.2.4 Cross-sectional research suggests that social closeness modulates INS

Taking a cross-sectional approach to understand social closeness and relationship development, some studies compare romantic couples, friends and strangers at single moments in time. Such studies suggest that the nature of a dyad's relationship influences INS during forms of interaction including joint motor action, conversation, and classroom learning (Bevilacqua et al., 2019; Djalovski et al., 2021; Long et al., 2022; Speer et al., 2024; Sun et al., 2021; Zhang et al., 2023). Djalovski et al. (2021) recruited romantic couples, friends and strangers to complete a finger tapping task as dyads, and a conversation-based empathy-giving task while brain activity was measured using EEG. During the finger tapping task, INS was greatest between romantic couples, followed by friends, and lowest between strangers. The authors suggest that cumulative joint experience with a specific partner enhances prediction of the partners movements, resulting in greater INS. The empathy-giving task revealed the opposite gradient with romantic couples showing the least INS, friends showing more, and strangers showing the most INS. Djalovski et al. propose that strangers monitor each other for potential negative responses more closely than couples to avoid the consequences of a potential misunderstanding. In another study examining verbal communication, Speer et al. (2024) recruited friends and strangers to engage in prompted conversations with demarcated turns. The authors report that across the span of conversation, friends showed decreasing INS and strangers showed increasing INS, with the reductions in INS corresponding to more exploratory conversations and increases in INS seeking to converge on common ground. Though phrased differently, Speer et al.'s interpretation is closely aligned to Djalovski et al.'s interpretation: The less well a dyad knows each other, the greater the INS during verbal communication. To explore this further, we highlight that a central difference between the motor and verbal communication tasks is that the motor task (i.e., drawing specific objects with an 'Etch A Sketch') is highly specified, setting both dyad members' expectations clearly and symmetrically, whereas the verbal communication tasks (i.e., describing a troubling or distressing event and conversing with demarcated turns) are temporally asymmetrical and inherently unpredictable. We propose that the degree of predictability of behaviour induced by the task contributes to the opposite INS gradients.

Other cross-sectional hyperscanning studies provide evidence that social closeness can shape the arousal that people experience while interacting, as well as INS. In a conversation study, Long et al.

(2022) recorded brain activity with fNIRS while participants engaged in supportive and conflictual conversation. The authors observed that romantic couples showed greater INS than control dyads when engaging in debate. INS was associated with dyads' arousal ratings, suggesting the dynamic range of arousal in conflict-related conversations with a romantic partner moderates INS. Further, Zhang et al. (2023) compared INS during a competitive button-pressing task performed by older romantic couples and older strangers and found that romantic couples were more competitive and showed greater INS than strangers (note: this is to our knowledge the only hyperscanning study that includes older adults). These studies suggest that dyads who are socially closer explore more of the 'dynamic range' of arousal.

Considered together, these studies suggest that when dyads made up of strangers meet for the first time and engage in a creative, unconstrained activity, such as drawing, INS is likely to be low. Across repeated encounters, INS levels are likely to increase. Drawing on Dikker's model simulating intergenerational INS, one would expect that generational constellations may impact INS levels and may interact with the trajectory of INS as dyads become socially closer.

1.3 Present study: Tracking intergenerational INS longitudinally, across repeated collaborative interactions

In this preregistered study (https://osf.io/hz6tm), we had three aims:

1. To characterise INS in intergenerational dyads made up of one young and one older adult.
2. To chart the trajectory of INS within same generation and intergenerational dyads, as relationships form across repeated social interactions.
3. To characterise the relationship between INS and differing levels of loneliness, as well as social closeness, and attitudes toward generations (i.e., one's own vs. other generations).

To achieve these aims, we recruited 31 intergenerational and 30 same generation dyads to complete a six-session art program. At each session, we collected measures of participants' loneliness and attitudes toward other generations, then recorded dyads' brain activity using fNIRS while they drew independently and collaboratively with oil pastels. We calculated INS using wavelet transform coherence (WTC) for all pairs of four regions of interest (ROIs), which were the bilateral IFG and TPJ. According to fNIRS best practices, we report both fNIRS signals (oxygenated haemoglobin [HbO] and deoxygenated haemoglobin [HbR]), with HbO results presented in the main manuscript and HbR results presented in the Supplementary Materials. We employed a Bayesian statistical analysis approach, according to which we make inferences based on 95% confidence intervals called 95% HPDs (highest posterior density region) rather than p-values. See Methods and Supplementary Materials for additional details including complete tables with estimates and 95% HPD, which we present separately from results text for ease of reading.

Our findings pertaining to INS in intergenerational and same generation dyads, tracked across 6 sessions in a real-world context resembling a community art program, deliver first insights into INS involving older adults, multi-session trajectories of INS, as well as INS' potential as a biomarker for tracking changes in loneliness and social closeness in budding relationships.

2 Results

2.1 Self-reported loneliness, social closeness, and attitudes toward generations

We first investigated how self-reported loneliness, social closeness within dyads, as well as attitudes towards generations differ between intergenerational and same generation dyads (Figure 1; Table 1).

Loneliness. Intergenerational dyads reported feeling substantially less lonely than same generation dyads. Feelings of loneliness decreased substantially for both groups across sessions, with no difference in rate. **Social closeness (OIS).** Intergenerational dyads reported substantially greater feelings of social closeness, compared to same generation dyads. Feelings of social closeness increased substantially across sessions for both groups, with no difference in rate. **Attitudes toward generations (allophilia).** Same generation dyads reported feeling substantially closer to their own generation than the intergenerational dyads, who reported feeling equally close to their own and the other generation. Allophilia scores stayed stable across sessions (i.e., no change observed).

Relationships between measures. Greater social closeness was substantially associated with reduced feelings of loneliness for same generation dyads and a matching trend was observed for intergenerational dyads. These associations did not differ between groups. Greater social closeness was substantially associated with more positive attitudes toward other generations for intergeneration dyads but not same generation dyads. This association showed a trending difference between groups. Greater loneliness was substantially associated with more positive attitudes toward other generations for same generation dyads but not intergenerational dyads. This association did not differ between groups.

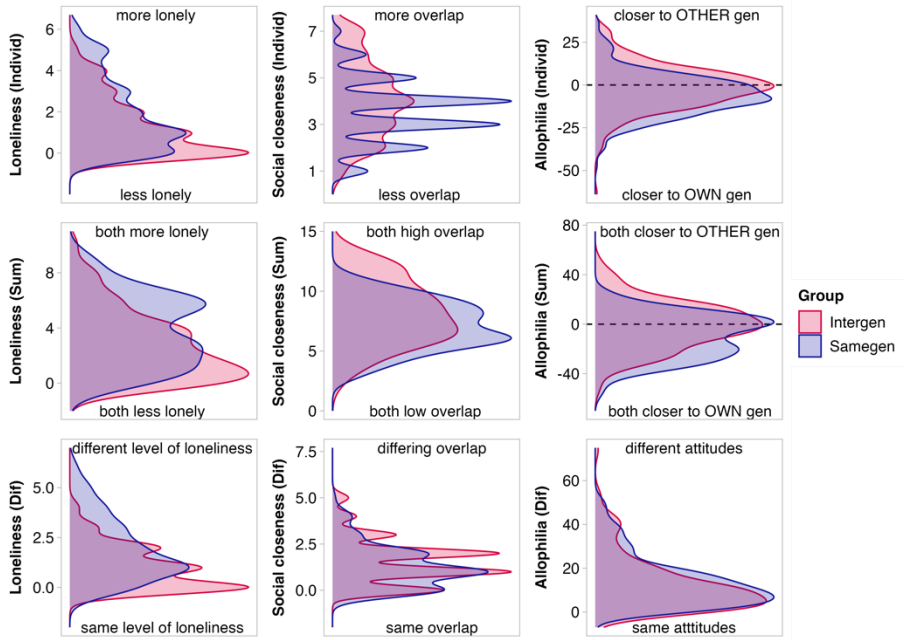

Figure 1. Top: Distributions of self-reported loneliness, social closeness (OIS), and attitudes toward generations (allophilia) of individual participants. Middle: Distribution of summed scores per dyad. Bottom: Distribution of difference scores per dyads.

Table 1. Unstandardised estimates computed per self-reported measure with 95% HPD in square brackets. Point estimates for all six sessions combined are presented first, followed by the estimates of the slope of change across sessions in the lower section. Self-report measures are loneliness, social closeness (OIS), and attitudes toward generations (allophilia). Visualisation by age (i.e., older or younger adult) and group in Supplementary Figure 1.

	Loneliness	Social Closeness	Allophilia
Sessions combined			
Intergenerational	1.28 [1.02, 1.54]	4.08 [3.76, 4.39]	-1.19 [-3.45, 1.05]
Same gen	1.89 [1.62, 2.16]	3.52 [3.19, 3.38]	
Intergen-Same gen	-0.61 [-0.99, -0.25]	0.56 [0.10, 1.00]	4.48 [1.29, 7.56]
Change across six sessions			
Intergenerational	-0.06 [-0.10, -0.02]	0.24 [0.19, 0.27]	-0.21 [-0.55, 0.12]
Same gen	-0.07 [-.11, - 0.03]	0.25 [0.20, 0.30]	-0.02 [-0.37, 0.30]
Intergen-Same gen	0.01 [-0.05, 0.07]	-0.01 [-0.08, 0.07]	-0.18 [-0.66, 0.28]

Table 2. Unstandardised estimates of relationship between self-reported measures per group with 95% HPD in square brackets. Self-report measures are loneliness, social closeness (OIS), and attitudes toward generations (allophilia).

	Loneliness	Social Closeness
Social Closeness (Intergen)	-0.13 [-0.27, 0.01]	
Social Closeness (Samegen)	-0.16 [-0.28, -0.04]	
Allophilia (Intergen)	0.01 [-0.00, 0.02]	0.02 [0.01, 0.04]
Allophilia (Samegen)	0.02 [0.01, 0.03]	0.01 [-0.01, 0.2]

2.2 INS

2.2.1 Real dyads vs. pseudo dyads

The first step in our analysis of INS was to perform contrasts between real and pseudo dyads for INS estimates reflecting all sessions combined and those reflecting change in INS across sessions per combination of ROI pair, task, and group. Contrasts serve to assess whether the level of observed INS (or the slope of change in INS) differs meaningfully from a null distribution of INS levels (or slopes) made of dyads who never interacted with one another. Further statistical analyses can then be performed on the ROI pairs where real dyads INS differed substantially from pseudo dyads' INS. We report estimates and contrasts with 95% HPD in Supplementary Tables 1-4.

INS levels for all sessions combined. We found that all substantial differences corresponded to greater INS for real than pseudo dyads (black squares in Figure 2A; solid lines in Figure 2B; Supplementary Table 2). The ROI pairs showing substantial differences were RIFG~RIFG for intergenerational dyads drawing alone, LIFG~LIFG, LTPJ~LTPJ, RIFG~RIFG, LIFG~RIFG, LIFG~LTPJ, RIFG~LTPJ for intergenerational dyads drawing together, no ROI pairs for same-generation dyads drawing alone, and LIFG~RIFG and RIFG~RTPJ for same-generation dyads drawing together. HbR analyses were similar, in that LTPJ~LTPJ, LIFG~RIFG, and LIFG~LTPJ showed substantial differences between real and pseudo dyads for intergenerational dyads drawing together (reported in full in Supplementary Materials).

Change in INS levels across sessions. We observed a more positive slope of change for all ROI pairs that differed substantially between real and pseudo dyads, with one exception (black squares Figure 3A; solid lines in Figure 3B; Supplementary Table 4). The ROI pairs showing substantial differences were LIFG~RTPJ for intergenerational dyads drawing alone, LTPJ~LPTJ and RIFG~RTPJ for intergenerational dyads drawing together, no ROI pairs for same-generation dyads drawing alone, and RTPJ~RTPJ and LIFG~LTPJ for same-generation dyads drawing together. HbR analyses showed little similarity (reported in full in Supplementary Materials).

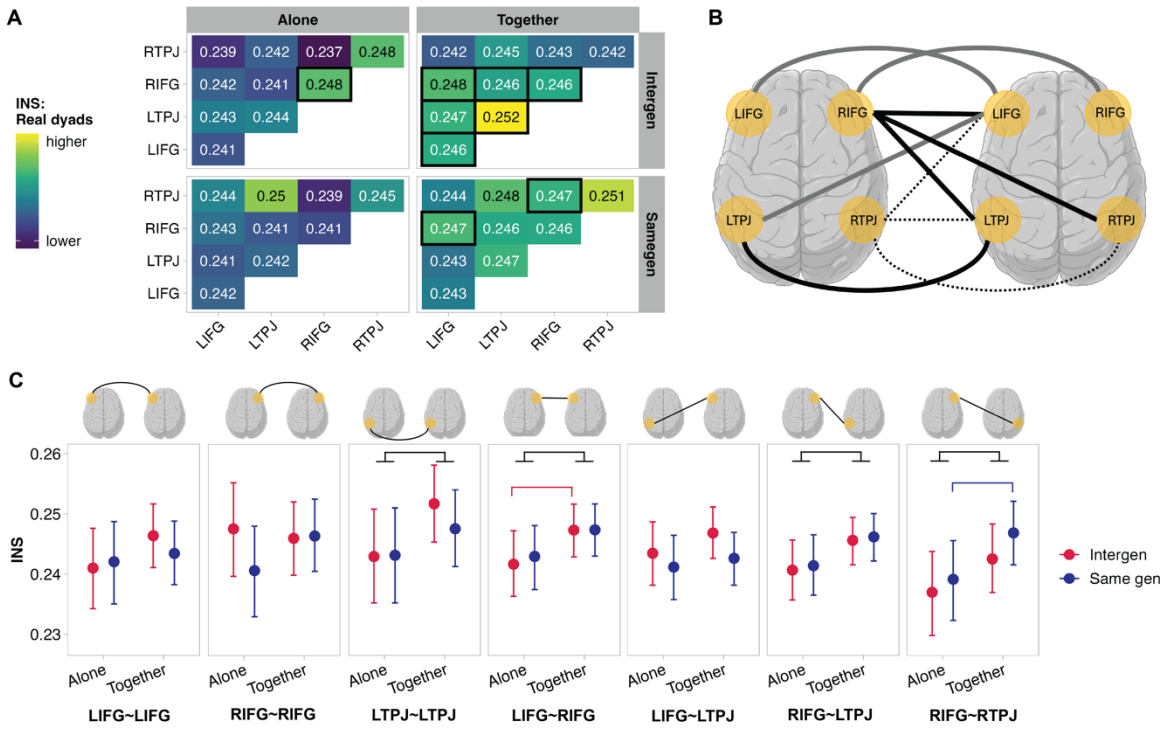

Figure 2. A) INS for all ROI pairs per task and group; black squares indicate that INS levels differ between real and pseudo dyads substantially (i.e., 95% HPD do not overlap). B) Visualisation of all possible ROI pairs (n=10). Dashed lines indicate ROI pairs where INS did not differ substantially between real and pseudo dyads. Solid lines indicate ROI pairs where INS differed substantially between real and pseudo dyads. Black solid lines indicate ROI pairs where task, group, and task*group contrasts showed substantial differences. Grey solid lines indicate ROI pairs where contrasts showed no substantial differences. C) INS levels with 95% HPD for all ROI pairs that differed between real and pseudo dyads, for which task, group, and task*group contrasts were computed. LIFG~LIFG: No differences. RIFG~RIFG: No differences. LTPJ~LTPJ: Task difference, drawing together > alone. LIFG~RIFG: Task difference, drawing together > alone. Interaction, drawing together > alone for intergenerational dyads. LIFG~LTPJ: No differences. RIFG~LTPJ: Task difference, drawing together > alone. RIFG~RTPJ: Task difference, drawing together > alone. Interaction, drawing together > alone for same generation dyads. Full list of estimates and contrasts with 95% HPD available in Supplementary Tables 1-2 for HbO. HbR analyses visualised in Supplementary Figure 2, showed the same pattern of results for LIFG~RIFG and RIFG~LTPJ.

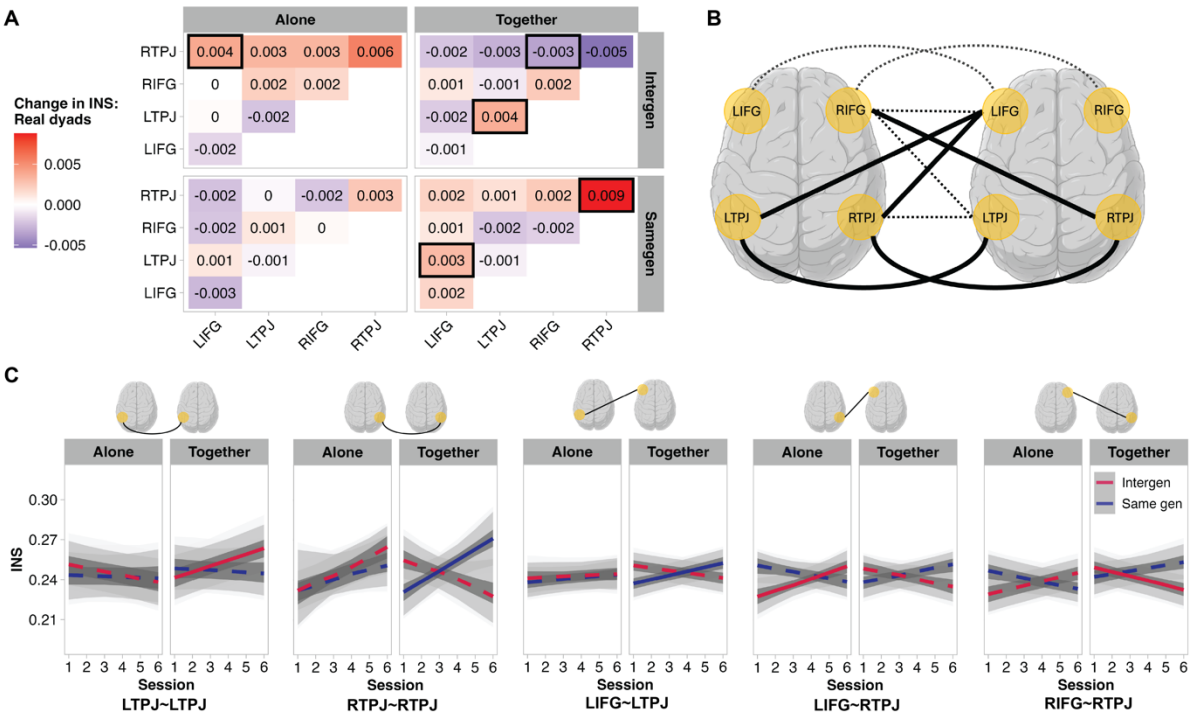

Figure 3. A) Slope of change in INS across six sessions; black squares indicate that INS levels differ between real and pseudo dyads substantially (i.e., 95% HPD do not overlap). B) Visualisation of all possible ROI pairs (n=10). Dashed lines indicate ROI pairs where the slope of change in INS did not differ substantially between real and pseudo dyads. Solid lines indicate ROI pairs where the slope of change in INS differed substantially between real and pseudo dyads. Black solid lines indicate ROI pairs where task, group, and task*group contrasts showed substantial differences. C) Slope of change in INS across sessions for all ROI pairs that differed between real and pseudo dyads, for which task, group, and task*group contrasts were computed. Solid lines indicate INS~Session relationship was substantial (i.e., 95% HPD does not overlap with 0). Dashed lines indicate non-substantial INS~Session relationships. Grey shading shows 95%, 89%, and 50% intervals of the posterior predictive distributions. LTPJ~LTPJ: Interaction effect, drawing together > alone for intergenerational dyads. RTPJ~RTPJ: Interaction effects, drawing together < alone for intergenerational dyads and intergenerational < same generation dyads for drawing together. LIFG~LTPJ: Group effect, intergenerational < same generation dyads. LIFG~RTPJ: Interaction effects, drawing together < alone for intergenerational dyads, intergenerational > same generation dyads for drawing alone, and intergenerational < same generation dyads for drawing together. RIFG~RTPJ: Interaction effects, drawing together < alone for intergenerational dyads, intergenerational > same generation dyads for drawing alone, and intergenerational < same generation dyads for drawing together. Full list of estimates and contrasts with HPD available in Supplementary Tables 3-4 for HbO. HbR analyses, visualised in Supplementary Figure 3, showed the same pattern of results for RTPJ~RTPJ and the same interaction effect of drawing together < alone for intergenerational dyads.

2.2.2 Composition of non-homologous ROI pairs in intergenerational dyads

For the intergenerational dyads specifically, we examined whether INS differed as a function of the generational composition of the ROI pairs. In other words, whether an ROI belonging to an older or younger member of a dyad influenced INS levels for all sessions or slopes across sessions. Full list of estimates and contrasts with HPD available in Supplementary Table 5.

INS levels for all sessions combined. When intergenerational dyads drew together, there was a trend of greater INS when the LIFG belonged to the older adult and the LTPJ belonged to the younger adult than vice versa. We observed no substantial differences in INS for any composition of any ROI pair for drawing alone. **Change in INS levels across sessions.** No substantial differences in the INS slopes across sessions for any composition of any ROI pair, for drawing alone or together.

2.2.3 Contrasting drawing conditions and groups

INS levels for all sessions combined. We observed no substantial differences between groups (i.e. group effect) but did observe task effects. We observed substantially greater INS for drawing together than alone in LTPJ~LTPJ, LIFG~RIFG, RIFG~LTPJ and RIFG~RTPJ (i.e., task effect). With respect to interaction between group and task, we found that in LTPJ~LTPJ, INS was substantially greater for drawing together than alone for intergenerational dyads. In RIFG~RTPJ, INS was substantially greater for drawing together than alone for same generation dyads. Parameter estimates per ROI pair, task and group visualised in Figure 2C. Full list of contrasts with 95% HPD supplied in Supplementary Table 6.

Change in INS levels across sessions. We observed no substantial difference between drawing alone and together (i.e., no task effects) but did observe the following group effect: We observed a substantially more positive INS slope for the same generation than the intergenerational dyads in LIFG~LTPJ. We also found several interactions effects. Intergenerational dyads showed a substantially more positive INS slope for drawing together than alone in LTPJ~LPTJ, and substantially more positive INS slopes for drawing alone than together in RTPJ~RTPJ, LIFG~RTPJ, and RIFG~RTPJ. This difference was substantial for drawing together, whereby the INS slope was more positive for same-generation dyads, relative to intergenerational dyads. Same-generation dyads further showed substantially more positive INS slopes than intergenerational dyads for drawing together in RTPJ~RTPJ, LIFG~RTPJ and RIFG~RTPJ. Intergenerational dyads showed substantially more positive INS slopes than same generation dyads when drawing alone in LIFG~RTPJ and RIFG~RTPJ. Parameter estimates per ROI pair, task and group are visualised in Figure 3C. Full list of contrasts with 95% HPD supplied in Supplementary Table 7.

2.2.4 Relationship between INS and self-report measures

Loneliness. *Summed.* We observed no substantial main, task, or group effect on the relationship between INS and summed loneliness scores. We observed an interaction effect in RIFG~RTPJ, for the intergenerational dyads, whereby the INS~summed loneliness relationship was substantially more negative for drawing alone than together (Figure 4; Supplementary Tables 10-11). *Difference.* No substantial main effect or group effects were observed. We observed a substantial effect of task for RIFG~RIFG, whereby the INS~loneliness difference relationship was substantially more negative for drawing together than alone. We observed substantial interaction effects for RIFG~RIFG, RIFG~RTPJ, and LTPJ~LTPJ. For RIFG~RIFG, we observed a substantial task difference for the intergenerational dyads only. For LTPJ~LPTJ, we observed a substantial task difference for intergenerational, but not same generation dyads and a substantial difference between groups for drawing alone but not together. For RIFG~RTPJ, we observed a substantial task difference for same generation dyads only (Figure 4; Supplementary Tables 12-13).

Social closeness (OIS). *Summed*. We observed a substantial positive relationship between summed social closeness scores and INS in RIFG~RTPJ (main effect). In LIFG~LIFG, we observed a substantial effect of task, whereby there was a substantially more positive relationship between INS and summed social closeness for drawing together than alone. We observed a group effect for RIFG~RIFG, whereby intergenerational dyads showed a substantially more positive relationship than same generation dyads, and RIFG~RTPJ where intergenerational dyads showed a substantially more negative relationship than same generation dyads. Substantial interaction effects observed for LIFG~LIFG and RIFG~RIFG, RIFG~RTPJ. In LIFG~LIFG there was a substantial task difference for same generation dyads only. In RIFG~RIFG the interaction effect showed a substantial group difference for drawing alone only. In RIFG~RTPJ, we observed a substantial task difference for the

same generation dyads only and a substantial group difference only when dyads drew alone (Figure 4; Supplementary Tables 14-15). *Difference.* No substantial main, task, or group effect on the relationship between INS and social closeness difference scores was observed. We did find a substantial interaction effect for RIFG~RIFG: There was a substantial task difference for both groups and a substantial group difference when drawing alone only (Figure 4; Supplementary Tables 16-17).

Allophilia. *Summed*. We observed a substantial negative relationship between summed allophilia scores and INS in LTPJ~LPTJ and LIFG~RIFG (main effect). We also found a substantial group effect for RIFG~RTPJ, where the relationship between INS and the summed allophilia scores was substantially more positive for the intergenerational dyads than same generation dyads. A substantial interaction effect was observed in LIFG~LTPJ, with a substantial task difference for intergenerational dyads only (Figure 4; Supplementary Table 18-19). *Difference*. No substantial main or group effects were observed. We observed a substantial task effect in RIFG~RIFG, where the relationship between INS and the difference in allophilia scores was substantially more positive for drawing together than alone. We found a substantial interaction effect for RIFG~RIFG, where we observed a substantial task difference for same generation dyads only (Figure 4; Supplementary Tables 20-21).

Figure 4. A) Slope of change in INS across levels of self-report measures for ROI pairs with at least one substantial relationship or substantial difference revealed by contrasts (for all ROI pairs see Supplementary Figures 5A-F; estimates and contrasts with 95 % HPD in Supplementary Tables 10-21). Lines indicate whether INS~Self-report measure relationship was substantial (solid) or non-substantial (dashed). Shading shows 95%, 89%, and 50% intervals for the posterior predictive distributions. Results of contrasts between task, group, and task*group contrasts for the panels above are as follows. *LIFG~LIFG Social closeness (Sum):* Task effect, negative relationship for drawing alone and drawing alone < together. Interaction effect, together > alone for same generation. *RIFG~RIFG Loneliness (Dif):* Task effect, drawing together < alone. *RIFG~RIFG Social Closeness (Sum):* Group effect, intergenerational > same generation dyads.

Interaction effect, intergenerational > same generation for drawing alone. *RIFG~RIFG Social Closeness (Dif):* Interaction effects, drawing together > alone for intergenerational dyads, drawing together < alone for same generation dyads, and intergenerational > same generation for drawing alone. *RIFG~RIFG Allophilia (Dif):* Task effect, positive relationship for drawing together and drawing together > alone. Interaction effect, drawing together > alone for same generation dyads. *LTPJ~LTPJ Loneliness (Dif):* Interaction effect, intergenerational < same generation dyads for drawing alone. *LTPJ~LTPJ Allophilia (Sum):* Main effect, negative relationship. Group effect, negative relationship for intergenerational dyads only. Task effect, negative relationship for drawing alone and together. *LIFG~RIFG Allophilia (Sum):* Main effect, negative relationship. Group effect, negative relationship for same generation dyads only. *LIFG~LTPJ Allophilia (Sum):* Interaction effect, drawing together < alone for intergenerational dyads. *RIFG~RTPJ Loneliness (Sum):* No differences. *RIFG~RTPJ Loneliness (Dif):* Interaction effect, drawing together < alone for same generation dyads only. *RIFG~RTPJ Social Closeness (Sum):* Main effect, positive relationship. Group effect, positive relationship for same generation dyads and intergenerational < same generation. Task effect, positive relationship for drawing alone. Interaction effects, drawing together < alone for same generation dyads, and intergenerational < same generation for drawing alone. *RIFG~RTPJ Allophilia (Sum):* Group effect, intergenerational > same generation dyads. B) Visualisation of all possible ROI pairs (n=10). Dashed lines indicate ROI pairs where i) neither INS for all sessions combines nor ii) the slope of change in INS differed substantially between real and pseudo dyads. Solid lines indicate ROI pairs where INS (for sessions combined or slope of change across sessions) differed substantially between real and pseudo dyads. Black solid lines indicate ROI pairs where task, group, and task*group contrasts showed substantial differences. Analyses of HbR, visualised in Supplementary Figure 4, showed similar pattern of results for Social Closeness (Sum) and Allophilia (Dif) in RIFG~RIFG, as well as Loneliness (Dif) in LTPJ~LTPJ.

3 Discussion

We invited intergenerational and same generation dyads to complete a six-sessions, resembling a community art program, and charted dyads' levels of loneliness, social closeness, attitudes toward generations and INS as they became acquainted across 6 sessions. Our first aim was to characterise INS within intergenerational dyads comprising one young and one older adult. In a large sample (sessions combined), we show that INS among intergenerational dyads is largely comparable to same generation dyads. Specifically, both dyad types show greater INS in LTPJ~LTPJ, LIFG~RIFG, RIFG~LTPJ, and RIFG~RTPJ for drawing together than alone, with the greatest differences in LIFG~RIFG for intergeneration dyads and RIFG~RTPJ for same generation dyads. Our second aim was to chart the trajectory of INS in same generation and intergenerational dyads, across repeated social interactions. While drawing together, ROI pairs that include the right TPJ (RTPJ~RTPJ, LIFG~RTPJ, and RIFG~RTPJ) showed decreasing INS for intergenerational dyads and increasing INS for same generation dyads. Our third aim was to characterise the relationship between INS and differing levels of loneliness, social closeness, and attitudes toward generations. We found that the relationship between loneliness and INS in RIFG~RIFG differed when dyads drew alone and together: Greater similarity in dyadic levels of loneliness predicted greater INS when dyads drew together and lower INS when they drew alone. Greater social closeness predicted increasing INS in RIFG~RTPJ for all dyads and greater INS in RIFG~RIFG for intergenerational than same generation dyads. With respect to dyadic attitudes towards generations, we observed that INS in LIFG~RIFG and LTPJ~LTPJ was elevated among dyads who felt further from other generations (i.e., closer to their own). Below, we explore the implications of these findings.

Individual's levels of loneliness and social closeness decreased and increased, respectively, across sessions, for both generational constellations. These findings match the target outcomes of the community programs proposed by policy makers, researchers, and health practitioners (Holt-Lunstad & Perissinotto, 2023; Scarpetti et al., 2024; WHO, 2021; Wigfield et al., 2022).

Considering all sessions together, we observed that the generational constellation (i.e., intergenerational vs. same generation) predicted differences in individual's levels of loneliness, social closeness and attitudes toward other generations. For example, simply being in the presence of a similar or quite differently aged person can alter one's perceptions of one's loneliness. If the other

person is of a similar age, one might feel more lonely than if the person is older, in which case one would self-report feeling less lonely – perhaps by virtue of social comparison (Arnold et al., 2021). This finding should be validated in future work by comparing intergenerational dyads with same generation dyads composed of two older adults, as well as two younger adults. Greater feelings of social closeness among intergenerational, as compared to same generation, dyads may relate to overcoming perceived generational differences or generational stereotypes (Galinsky et al., 2005). Notably, the distributions of difference in social closeness did not differ between groups (Figure 1), suggesting that the increased social closeness observed for intergenerational dyads was not driven by older or younger adults' responses alone, but rather by both age groups. Intergenerational dyads held more charitable attitudes toward other generations than same generation dyads (Figure 1), aligning with findings that contact with older adults reduces younger adults' negative stereotypes of and anxiety regarding older adults (Liao et al., 2023). Among intergenerational dyads, individuals' attitudes toward generations were linked to their social closeness ratings, highlighting possible bidirectional interplay between attitudes and social closeness. Moreover, among same generation dyads, greater loneliness was associated with a weaker preference towards one's 'own' (younger) generation, highlighting the window of opportunity for intergenerational social activities in combatting loneliness.

This study offers novel insights into INS during collaboration in dyads composed of older and younger adults, adding rich empirical data to the two existing studies that involve older adults (Dikker et al., 2024; Zhang et al., 2023). The fNIRS hyperscanning literature on collaboration focuses on the prefrontal and inferior frontal cortices and the TPJ (Czeszumski et al., 2022). The bilateral IFG play a role in the initiation and reception of joint attention (Koechlin et al., 2003; Redcay et al., 2012; Yoshioka et al., 2021) and the bilateral TPJ are central to the integration of social information (Jacoby et al., 2016; Saxe & Kanwisher, 2003). Moreover, with some exceptions (e.g., Zhang et al., 2023), hyperscanning studies typically only report homologous pairs of brain areas (e.g., LIFG~LIFG), for which the interpretation of heightened INS may be simpler. We preregistered and now report analyses of INS that include non-homologous ROI pairs (e.g., LIFG~RIFG) and offer possible reasoning for observations of heightened INS.

In our large sample (all sessions combined), we show that INS in intergenerational dyads is largely comparable to same generation dyads. That is, we observed greater INS in LTPJ~LTPJ, LIFG~RIFG, RIFG~LTPJ, and RIFG~RTPJ for drawing together than alone. This aligns with the existing findings that collaboration co-occurs with greater INS in brain regions that process social information. We interpret these findings as evidence that collaborative drawing results in heightened integration of social information (LTPJ~LTPJ), joint attention (LIFG~RIFG), and perhaps integration of the other person's maintenance of joint attention as social information (RIFG~LTPJ and RIFG~RTPJ). We also observed robust differences in INS while drawing together and alone in separate ROI pairs for each group: LIFG~RIFG for the intergenerational dyads and RIFG~RTPJ for the same generation dyads. We cautiously speculate that intergenerational dyads' level of cognitive control while drawing together is particularly high and aligned within dyads, and that same generation dyads may evaluate and integrate information regarding the strength or continuity of their partner's joint attention. This interpretation requires further investigation using paradigms that can quantify joint attention and cognitive control.

INS in IFG is proposed by some researchers to be unique to verbal communication, while a few studies show that INS in IFG may also play a role in non-verbal communication (Czeszumski et al., 2022). With our very large sample, we can provide strong evidence that INS involving the IFG occurs during non-verbal communication, such as silent collaborative drawing.

Cross-sectional studies suggest that INS levels during collaboration decrease with higher levels of familiarity (such as friendship or stable romantic relationships) that require repeated social interactions to establish (e.g., (Bevilacqua et al., 2019; Djalovski et al., 2021; Long et al., 2022; Speer et al., 2024; Sun et al., 2021; Zhang et al., 2023). Sened et al.'s (2025) proof-of-concept study reports the INS trajectories of eight dyads at three (in a series of six) therapeutic sessions. Sened et al. find increasing INS in bilateral IFG across the three sessions, while clinician-patient dyads completed imagery and cognitive behavioural training procedures. We document INS trajectories during collaboration and independent drawing by two (initial) strangers with the highest temporal granularity to date – 6 consecutive time points. Our findings provide clear evidence of INS changes from a dyad's first encounter to the final recorded session, entailing ~6 hours of time spent together and ~90 minutes of collaborative activity spread across 6 weeks.

We observed that while dyads drew together, ROI pairs that include right TPJ (RTPJ~RTPJ, LIFG~RTPJ, and RIFG~RTPJ) showed decreasing INS among intergenerational dyads but increasing INS among same generation dyads. This may suggest that, in the context of collaborative drawing, intergenerational dyads' monitoring and integration of their partner's levels of joint attention may decrease with increasing familiarity, whereas same generation dyads may monitor each other's levels of joint attention more closely as familiarity increases. Across sessions, INS increased in RTPJ~RTPJ for same generation dyads and LTPJ~LTPJ for intergenerational dyads. This difference in lateralisation may be related to the integration of "matched" or "mismatched" predictions. Whereas the right TPJ is associated with identifying "mismatched" predictions, the left TPJ encodes both "matched" and "mismatched" predictions (Doricchi et al., 2022). Accordingly, it is possible that same generation dyads become increasingly sensitive to "mismatched" predictions with increasing familiarity while intergenerational dyads may encode more "matched" predictions with increasing familiarity. Alternatively for intergenerational dyads, the frequency or absolute amount of mismatched predictions may decrease with increasing familiarity.

We found that the relationship between loneliness and INS in RIFG~RIFG differed when dyads drew alone and together: Greater similarity in dyadic levels of loneliness predicted greater INS when dyads drew together and lower INS when they drew alone. This may point to how differences in loneliness can shape joint attention. Experiences of loneliness predict changes in cognition, such as perceptual speed, memory, and negatively biased perceptions of social information (Ayalon et al., 2016; Cachón-Alonso et al., 2023; J. T. Cacioppo & Hawkley, 2009; Okruszek et al., 2021; Spithoven et al., 2017). It follows that these changes in cognition may co-occur with changes in joint attention or may alter the facility with which individuals engage in joint attention (Corbin & Dhand, 2024). It is possible that lonelier individuals may require more numerous neural resources to maintain joint attention or alternatively present hypervigilant tendencies, both of which could result in elevated INS in RIFG~RIFG (Brilliant et al., 2022; Hampshire et al., 2010; Saporta et al., 2022). Further investigation should establish the extent to which this differential pattern of INS in RIFG~RIFG during collaborative and independent tasks can be used as a biomarker of loneliness in research and real community programs aiming to combat loneliness (Ahkter-Kahn & Au, 2020; Pan & Cheng, 2020).

To understand INS beyond the changes in familiarity incurred by repeated social interactions, we examined the extent to which dyads' self-reported feelings of social closeness were reflected in INS. We observed that greater reported social closeness predicted greater INS in RIFG~RTPJ for all dyads and in RIFG~RIFG for the intergenerational dyads. We interpret the increasing INS in RIFG~RTPJ as meaning that dyads who feel close to one another monitor and integrate each other's joint attention more than dyads who feel less socially close. The increasing INS for intergenerational dyads in

RIFG~RIFG may reflect joint attention as well as heightened arousal or the facilitation of joint attention via heightened arousal (Bast et al., 2025; Lachat et al., 2012; Long et al., 2022; Zhang et al., 2023). INS may be useful as a biomarker for changes in social closeness across repeated social interactions for all adults of all ages, though potentially more robust for same generation dyads.

With respect to dyadic attitudes towards generations, we observed that INS in LIFG~RIFG and LTPJ~LTPJ decreased as feelings of closeness to other generations increased. As this analysis is particularly exploratory in nature, with no empirical precedent, we offer a tentative suggestion that similarity in attitudes towards generations may give dyads a more internally consistent basis upon which they form predictions about each other's behaviour (i.e., elsewhere termed "common ground"; Speer et al., 2024). These findings can serve as a point of departure for research examining the impact of different sources of 'common ground' on INS. For example, studies could explore whether cumulative life experience (e.g., number of years lived) gives older adults an advantage for finding common ground and/or whether similarities in socialisation (e.g., culture, age, socio-economic status, hobbies) play bigger role in establishing common ground that could shape INS.

As recommended by Simons et al. (2017), we make explicit the constraints on generality of this work. Our findings only generalise to the targeted brain regions (i.e., bilateral IFG and TPJ). Though our study offers typical coverage for fNIRS hyperscanning studies, we encourage the use of high-density fNIRS optode arrays in future research on this topic (Shuo et al., 2025). We observed overlap between HbO and HbR results for analyses of all sessions together and INS trajectories across sessions, with some overlap in HbO and HbR results for relationships between INS and self-reported measures. Our adequate pairing of sample size and conservative Bayesian approach notwithstanding, we encourage other researchers to replicate these findings. Moreover, the INS self-report measures are not necessarily generalisable across cultures, due to differences in formation of relationships (Goodwin, 2013; Lu et al., 2021). Though our findings pertaining to changes in loneliness and social closeness across sessions are in line with findings from behavioural and qualitative studies performed as part of more elaborate and enriching community art programs, our sessions were attended by one dyad at a time, with partners assigned based on availability. Future studies could expand our paradigm to small group sessions with multiple dyads and free partner choice to reflect community programs more closely. We have no reason to believe that the results depend on other characteristics of the participants, materials, or context.

One limitation of this study is that we did not have the resources to include a group of same generation dyads composed of two older adults, though this would have been the optimal design. Without such a group, we cannot be sure that differences between groups are purely related to the generational constellation and not age-related differences in neural processing. Future research should compare same generation dyads across different age ranges. A second limitation of this study is that three optodes of one Photon Cap device unexpectedly became defective partway through data collection (and were replaced as rapidly as possible). This resulted in the exclusion of several participants' right TPJ channels for the affected sessions. Thus, the number of data points for ROI pairs involving right TPJ, particularly RTPJ~RPTJ, is lower than for other ROI pairs (Supplementary Figure 7). Our Bayesian approach accounted for this difference in sample size per ROI pair by partial pooling (for an excellent tutorial, see: Nalborczyk et al., 2019).

4 Conclusion

The study met its overarching aim of developing the evidence base for intergenerational community programs aiming to combat loneliness. Specifically, we documented INS in intergenerational dyads

including older adults, charted the trajectory of INS from first meeting to greater levels of familiarity while intergenerational and same generational dyads engaged in collaborative and creative activity, thus demonstrating the promise of INS as a biomarker for predicting changes in loneliness.

5 Methods

5.1 Participants

We recruited 122 community-dwelling participants from Zurich, Switzerland. Of these, 31 were older adults (aged 69+ years) and 91 were younger adults (aged 18–35 years). We assigned participants to intergenerational dyads (n = 31) and same generation dyads (n = 30) based on availability for sessions (e.g., matching people available at the same day/time for 6 consecutive weeks). Due to the logistical challenge posed by recruiting for and scheduling a multi-session study of this scale, gender pairings were not prioritised (see Supplementary Figures 8 and 9 for summary of gender pairings and session spacing). Intergenerational dyads consisted of an older adult (76 ± 4 years); 18 female, 13 male) with a younger adult (24 ± 4 years; 19 female, 11 male, 1 other). Same generation dyads consisted of two younger adults (22.5 ± 3.6 years; 36 female, 24 male). All dyads started the study as strangers. To be included, participants had no known history of neurological or psychological disorders (e.g., stroke, concussion, ADHD, autism, schizophrenia, depression) and were fluent in German.

We recruited participants via the University of Zurich's Healthy Longevity Centre, ETH Zurich's DESCIL student pool, clubs and organizations for senior citizens (e.g., theatre groups and choirs), and social media. We obtained written informed consent from all participants. Ethical approval was obtained from the Ethics Committee of the Canton Zurich (Ref: 2023-01073). The study was conducted according to the Declaration of Helsinki.

5.2 Measures

5.2.1 Self-report measures

Loneliness. Participants completed the *6-Item Scale for Overall, Emotional, and Social Loneliness* (De Jong Gierveld & van Tilburg, 2006) at the beginning of each session.

Social closeness. Participants indicated how socially close they felt to the other member of their dyad using the *Inclusion of Other in the Self Scale* (Aron et al., 1992) at the end of each session. This measure uses Venn diagrams with incremental increases from no overlap to complete overlap as visual analogue representation of social relationships.

Attitudes toward other generations. The *Allophilia Scale* (Pittinsky et al., 2011) is typically used to characterise participants' attitudes toward an outgroup (e.g., people of another ethnicity or political leaning). We adapted this scale in three variants: a) "younger people", "older people", and "people my age". At the beginning of each session all participants completed the scale with "people my age". Then older adults completed the scale with "younger people" and younger adults completed the scale with "older people". To obtain baseline-corrected attitudes towards other generations, we subtracted each participant's score for "people my age" from their score for the age group they did not belong to.

5.2.2 fNIRS recordings

We recorded fNIRS signals using two Cortivision Photons Cap (Cortivision sp. z o.o., Lublin, Poland) and Cortivew software. Each device had 16 LED sources, which emitted wavelengths of 760 and 850 nm, and 10 detectors (26 optodes in total). The sample rate was 4-6 Hz. We positioned optodes according to the 10-5 EEG positions (Oostenveld & Praamstra, 2001) over bilateral IFG and TPJ based on MNI-space coordinates derived from the Neurosynth database (https://neurosynth.org/). Specifically, we used the search terms 'ifg' and 'tpj' and recorded the coordinates of the area with the highest activation in each the left and right hemisphere, defining the 'centre' of our ROIs. There were the following: *left IFG:* -48, 22, 8; *right IFG:* 50, 22, 16; *left TPJ:* -56, -54, 20; and *right TPJ:* 56, -52, 18. See Supplementary Figure 10 for visualisation of ROI centre coordinates and Supplementary Figure 11 for optode arrangement.

Digitisation of optodes. After placement of the cap according to fiducial markers and before attaching optodes, we recorded a 3D image of each participant's head using Structure Sensor Pro (model SA39) attached to an Apple iPad Pro (v. 10). The 3D head scan was processed using MATLAB (v. 2023b) and the Fieldtrip toolbox (Oostenveld et al., 2011; Appendix 4). Labels for all detectors and sensors and fiducial reference points were assigned to the 3D head scan and then co-registered to MNI space. Next, we obtained the interoptode distance per channel, the coordinates of the point of measurement between optodes making up each channel, as well as distance from the point of measurement to the centre of the ROI. See Supplementary Figure 12 for visualisation of optode distances from ROI centres.

5.3 Procedure

Dyads attended six sessions, with approximately one week between sessions (Supplementary Figure 9 shows schedule of sessions and number of days between sessions per dyad). Sessions were led by a female lead-researcher who provided instructions following a script (available on OSF: https://osf.io/zms2v) and answered participants' technical and scientific queries. A second female researcher was present to aid with technical steps and did not speak unless directly addressed. Both researchers politely deflected participants' social inquiries.

The order of events at each session is visualised in Figure 5A. At the beginning of each session, dyads completed self-report measures of loneliness and attitudes towards generations (allophilia) on an iPad, with a felt divider between participants providing privacy. Then the fNIRS caps were placed on participants' heads and the second researcher recorded 3D models of each participant's head with cap on (participants instructed to sit very still while researcher circled participant with 3D scanner). Next, the lead researcher reminded that participants could converse at any time except while drawing. The researchers attached optodes to the caps, ensuring that optodes came in direct contact with the scalp by clearing hair. Then fNIRS devices were turned on, paired with recording laptops (n = 2) and fNIRS signals were verified for best possible calibration. Video recording was initiated (one GoPro11 Black was positioned with a direct view of participants as shown in Figure 5B, to allow for future motion tracking analyses).

Next, participants drew three drawings with oil pastels, without talking. Participants were instructed that they would have 5 min to draw anything they liked, and that they would complete the first drawing alone and the second and third together on a single piece of paper. No further instructions were provided (e.g., no suggestions for motifs). While participants drew alone, they were separated by a felt divider, ensuring that they could not see each other. The divider was removed when they drew together. In cases where participants conversed to plan their drawings, the researchers waited

for a natural pause to begin the 5 min timer. Each drawing was labelled and digitised after the session.

Following the three drawings, the participants completed a short collaborative activity (different at each session to keep participants motivated). Then, fNIRS recordings were stopped, and still wearing the fNIRS caps, participants completed a self-report measure of social closeness (OIS) and provided written commentary on their experience in the session (Figure 5A). After the final session, the lead researcher held a semi-structured interview with each participant individually to gain qualitative insights into the participant's experience.

Self-report measures were administered via RedCap®. fNIRS recordings were synchronised using triggers sent from PsychoPy (v. 2022.2.5; Peirce et al., 2022) marking the beginning of each drawing and the collaborative activity.

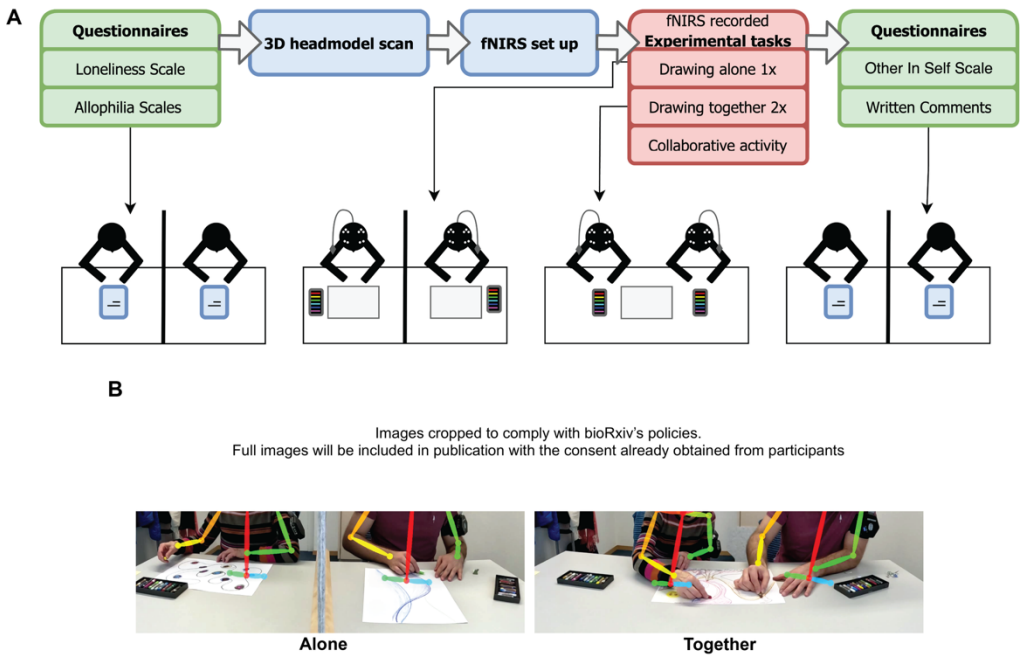

Figure 5. A) Flowchart visualising procedure for selecting which channels to include in analysis for individual participants, preprocessing steps for individual participants and calculation of wavelet transform coherence (WTC) for dyads. B) Left: An intergenerational dyad drawing alone on separate pages with a grey felt divider between them, blocking their view of each other. Right: The same intergenerational dyad drawing together on one page. The overlay of colourful lines shows the 2D motion tracking, which was captured, but is not reported here.

5.4 Data analysis

5.4.1 Interbrain synchrony

5.4.1.1 Individual level

Channel selection. We aimed to record from the identical position on participants heads at each session, however due to the stretchy nature of neoprene caps and the inevitability of hair growth/haircuts, optode positions varied from session to session. To overcome this challenge, we prioritise proximity to the centre of each ROI (De Felice et al., 2024). That is, for each participant at each session, we selected the best channel per ROI. First, we excluded channels without visible

cardiac rhythms (~1 Hz), with a scalp-coupling index (SCI; Pollonini et al., 2014) of <.7 for frequencies between 0.7-1.35 Hz, and with an interoptode distance <20 mm or >40 mm. Next, we ranked the remaining channels by distance from the centre of the ROI (closest to furthest) and selected the closest channel as the 'best channel' (Figure 6A). See Supplementary Table 0 for description of number of recordings and sessions excluded, as well as reasons with for exclusion.

Preprocessing. We preprocessed the fNIRS signals using MNE (version 1.71; Gramfort et al., 2013, 2014), MNE-NIRS (version 0.71; Luke et al., 2021). As summarised in Figure 6A, the signal was converted from raw intensity to optical density. Motion artefacts were corrected using the temporal derivative distribution repair algorithm (Santosa et al., 2019) and short channel regression was applied using the short channel with the highest SCI (Luke et al., 2021). Next, the signal was converted to concentrations of HbO and HbR using the Modified Beer–Lambert law (Delpy et al., 1988; Kocsis et al., 2006) using an age-specific partial pathlength factor to account for age-related differences in the biological tissues probed by NIR light (Garcia-Castro, n.d.; Scholkmann & Wolf, 2013). This algorithm is suitable for participants aged 0-70 years. For participants aged >70 years, we specified the age parameter as 70. Last, a bandpass filter from 0.015 to 0.4 Hz was applied.

5.4.1.2 Dyad level

Wavelet transform coherence (WTC). We computed INS values for all possible ROI pairs (N = 10; homologous ROI pairs = LIFG~LIFG, RIFG~RIFG, LTPJ~LTPJ, RTPJ~RTPJ; non homologous ROI pairs = LIFG~RIFG, LIFG~LTPJ, LIFG~RTPJ, LTPJ~RTPJ, RIFG~LTPJ, RIFG~RTPJ) for each real dyad and pseudo dyad (Figure 6A). Pseudo dyads are dyads made by pairing participants who never interacted, but align with our group types (e.g., both younger adults, or one older and one younger adult). We computed INS values for pseudo dyads to obtain a null distribution against which to compare INS in real dyads. Differences in INS between real and pseudo dyads for specific ROI pairs indicate that INS levels are the result of the real interactions of real pairs and do not occur spuriously between any two people completing the same tasks in the same setting. WTC was computed using HyPyP (version 0.5.0b11; Ayrolles et al., 2021) with a complex Morlet wavelet, for which the period range was defined as 5-50 seconds (0.02-0.2 Hz).

5.4.1.3 Group level

For our preregistered statistical analyses, we followed a Bayesian approach to multi-level regression (McElreath, 2020). We fit multi-level models using the brms package (version 22.2; Bürkner, 2017) in the R language (version 4.5.1; R Core Team, 2022) within the RStudio IDE (version 2025.05.1+513; RStudio Team, 2020). From these models, we report and interpret the posterior distribution of key parameters using a 95% credible interval, calculated via the 95% highest posterior density region (HPD) method (McElreath, 2020). For readers more accustomed to a Frequentist approach that presents p-values, we recommend perusing Kruschke & Liddell (2018), and we offer the following (simplified) heuristic for interpreting 95% HPDs: Parameter and comparison estimates can be said to be *substantial* when the 95% HPD does not contain zero and to be trends when the tip of an 95% HPD-tail overlaps with zero.

Self-report measures. To assess the extent to which loneliness, social closeness, and attitudes toward generations change across the six sessions, we fit the following model for each self-report measure separately, using individual scores (i.e., not dyadic sum or difference scores): *Score ~ 1 + Group * Session + (1|DyadID/ParticipantID)*. We subsequently computed contrasts between groups (intergenerational vs. same generation).

INS for sessions combined. We first sought to establish which, if any, ROI pairs showed substantially different INS levels for real dyads relative to pseudo dyads. We fit separate models for each ROI pair (n = 10), task (n = 2; drawing alone or drawing together), and group (n = 2; intergenerational or same generation): *INS ~ Dyad Type * Session*, where *Dyad Type* refers to real and pseudo dyads. Contrasts between real and pseudo dyads per model identified the ROI pairs for further analysis (Figure 6B).

Changes in INS across sessions. We first sought to establish which, if any, ROI pairs showed substantially different INS trajectories across sessions for real dyads relative to pseudo dyads. We fit separate models for each ROI pair (n = 10), task (n = 2; drawing alone or drawing together), and group (n = 2; intergenerational or same generation): *INS ~ Dyad Type * Session*, where *Dyad Type* refers to real and pseudo dyads. Contrasts between real and pseudo dyads per model identified the ROI pairs for further analysis (Figure 6B).

Further analyses with identified ROI pairs. We first fit models to assess whether intergenerational dyads show any directionality for non-homologous ROI pairs (e.g., high INS for older adult's left IFG and younger adult's right IFG, but not the inverse). Next, we fit one model for all sessions combined and one for changes across sessions including only real dyads and the respectively identified ROI pairs (models shown second tier of Figure 6B). We computed planned contrasts to examine the effect of task (drawing alone vs. drawing together), group (intergenerational vs. same generation), and the interaction between task and group. Finally, we fit a model (shown in second-last tier of Figure 6B) to all ROI pairs identified (sessions combined and across sessions) to examine the extent to which self-report measures of loneliness, social closeness (OIS) and attitudes toward generations (allophilia) predict levels of INS. To capture dyadic aspects of each measure, we included summed and absolute difference scores per dyad (Boukarras et al., 2025; Kenny et al., 2006). We report HbO findings in the main report and HbR findings in the Supplementary Material, with commentary on commonalities throughout the main report.

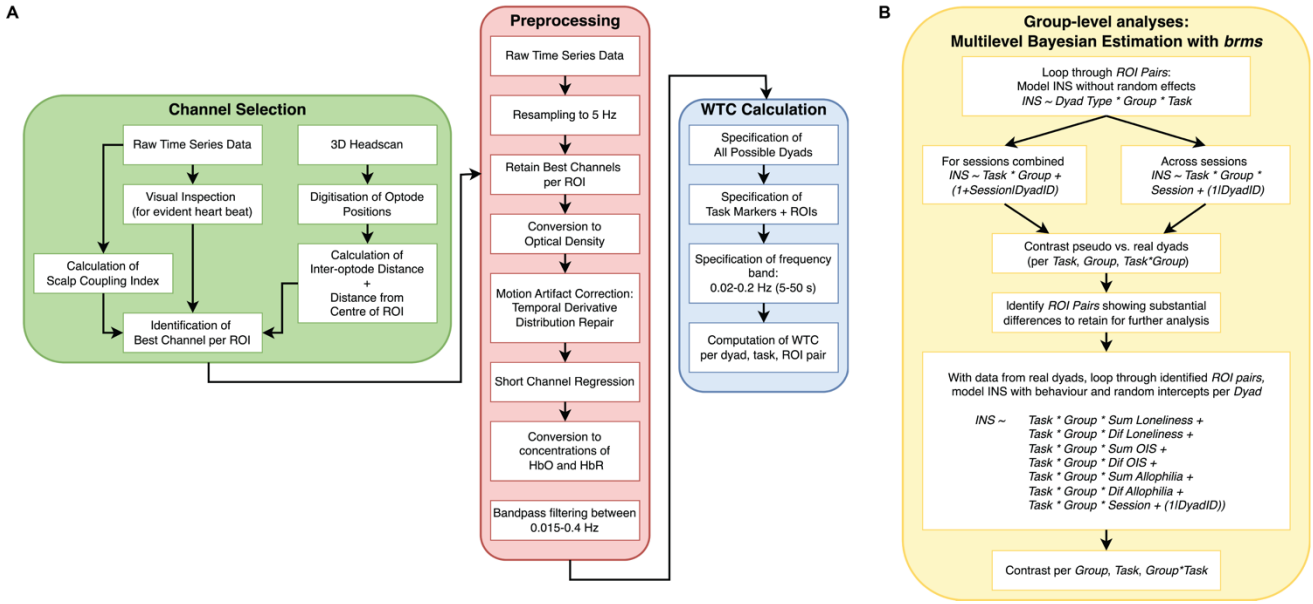

Figure 6. A) Flowchart visualising the procedure for selecting which channels to include in analysis for individual participants, preprocessing steps for individual participants and calculation of WTC for dyads. B) Flowchart visualising the order in which group-level analyses were performed in the R package brms, and showing the models fit.

Author contributions

RM: Conceptualization, equipment donation, data curation, formal analysis, Investigation, Visualization, Writing – original draft. GD: Methodology, Software, Writing – review & editing. ESC: Conceptualization, funding acquisition, Project administration, Writing – review & editing.

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Conflict of interest

The authors declare no potential conflict of interest.

Data availability statement

These data were collected after the submission of the following preregistration: https://osf.io/hz6tm. The data collected and analysed for this study can be found in our repository entitled 'Longitudinal perspectives on intergenerational inter-brain synchrony' on OSF: https://osf.io/xcgp6/.

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