Altered Cooperative Behavior and Inter-brain Neural Mechanisms in Older Adults: Evidence from Near-infrared Hyperscanning

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Abstract

Cooperation is crucial for the development of human society. Currently, the world has fully entered an aging society with a shortage of human resources, necessitating increasingly greater participation of older adults in social production activities. In this context, investigating the cooperative behavior of older adults holds practical significance. This study employed a modified cooperative button-pressing paradigm and near-infrared spectroscopy (fNIRS) hyperscanning technology to investigate changes in cooperative behavior among older adults and the underlying dual-brain neural mechanisms. The results revealed that after multiple trial-based learning, older adults could achieve the same level of cooperation as younger individuals. Exploratory psycho-neural mechanism analyses demonstrated that cooperative behavior in older adults relied more heavily on neural activity similarity pertaining to the task itself, whereas in younger individuals, it was more closely associated with personality trait similarity. Furthermore, younger dyads exhibited a leader during cooperation, while information flow in older dyads displayed bidirectionality. These findings provide developmental perspective evidence for our understanding of human cooperative behavior, while also indicating that the cooperative capacity of older adults is comparable to that of younger individuals, and may even be more inclusive. Older adults can still participate in social development and construction involving cooperation, thereby contributing to the maintenance of demographic dividends.

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Response: With global population aging intensifying and labor forces contracting, investigating whether older adults can achieve the same level of cooperation as younger adults despite cognitive decline and self-concept crystallization holds strong practical significance. Moreover, examining age-related differences in cooperative behavior and neural activity provides a developmental perspective for deepening our understanding of cooperation mechanisms and refining cooperation theories. Specifically, this study involves two innovations: (1) It is the first to use fNIRS hyperscanning to reveal changes in older adults' cooperative behavior and characteristics of inter-brain synchrony; (2) It employs representational similarity analysis to elucidate differences in the psycho-neural mechanisms between older and younger adults during cooperation.

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Response: This is an experimental study.

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Response: Previous studies using this paradigm for two-way mixed-effects ANOVA reported a significant interaction effect size of partial $^2 = 0.48$ (Cheng et al., 2015; Pan et al., 2017). Based on this, G*Power 3.1.9.7 analysis showed that 12 dyads were needed to achieve 80% statistical power (α = 0.05). This study recruited and formed 27 dyads, exceeding this requirement. Additionally, post-hoc power analysis using G*Power showed that the statistical power (1-β) for our core results—ANOVA interaction effects, age group main effects, and inter-brain synchrony t-tests—all exceeded 0.8, indicating adequate sample size.

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Response: We reported excluded data and reasons in detail: fNIRS data from 2 young adults were excluded due to equipment failure during data collection. Additionally, outlier trials with reaction times exceeding $±$3 SD from each subject's mean were removed.

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Changes in Cooperative Behavior and Underlying Dual-Brain Neural Mechanisms in Older Adults: Evidence from fNIRS Hyperscanning

Abstract

Cooperation is essential for human social development. As the world faces comprehensive population aging and labor shortages, older adults are increasingly needed to participate in social production activities. Investigating cooperative behavior in older adults thus holds practical significance in this context. This study employed a modified cooperative button-pressing paradigm and functional near-infrared spectroscopy (fNIRS) hyperscanning to explore age-related changes in cooperative behavior and underlying dual-brain neural mechanisms. Results revealed that older adults could achieve the same level of cooperation as young adults after multiple learning trials. Psycho-neural mechanism analyses showed that older adults' cooperation relied more on neural activity similarity during the task itself, whereas young adults' cooperation was more associated with personality trait similarity. Furthermore, young adults exhibited a leader-follower pattern during cooperation, while older adults showed bidirectional information flow. These findings provide developmental perspective evidence for understanding human cooperative behavior and suggest that older adults' cooperative abilities are comparable to those of young adults, even showing greater inclusivity. They can still participate in social development involving cooperation and contribute to maintaining the demographic dividend.

Keywords: cooperation; older adults; fNIRS hyperscanning; inter-brain synchronization; personality traits

Introduction

Cooperation plays a crucial role in human civilization. The establishment of human society is inseparable from cooperation, whether in hunting and gathering activities in primitive societies or in production and innovation processes in modern societies. Through cooperation, humans can utilize resources more effectively and improve productivity and quality of life (Sachs et al., 2004). Currently, the world has entered a comprehensive aging society, with the proportion of working-age population gradually declining and labor resources becoming strained. Social development requires greater participation from middle-aged and older adults. To address social development issues brought by population aging, strategies such as "delayed retirement" have been implemented in many countries and regions. In this social context, studying changes in older adults' cooperative behavior and their neural mechanisms is of important practical significance for tapping into the social potential of older adults and stimulating social vitality.

Cooperative behavior is widespread and diverse in social life. Related theories have explained cooperative behavior from different perspectives including social psychology, evolution, and economic games (Axelrod & Hamilton, 1981; Cosmides, 1989; Nowak, 2006; Ostrom, 2000). Among them, Social Identity Theory (Tajfel, 1974) posits that individuals define their identity through social belonging, thereby influencing their attitudes and behaviors. Specifically, individuals perceive and compare characteristics between themselves and given group members, 归属到具有相似特征的群体中，并表现出趋同行为。在合作任务中，当个体感到自己与群体有较高的相似度时，他们更倾向于表现出合作行为，以维护和增强群体的整体利益。从发展的视角而言，在年老化过程中，社会认同的需求在发生改变：年轻人处于自我概念的形成和巩固的阶段，通过与他人进行比较和合作的过程中建立自我价值和归属感 (Turner et al., 1992)，与 "相似" 的搭档进行合作有助于提高合作质量 (Giang et al., 2012; Zhu & Yi, 2024)；而老年人已经形成了稳定的自我认同和社会角色，相比于年轻人较少关注合作伙伴的相似性，而更关注任务本身 (Jackson & Balota, 2012)。同时老年人丰富的生活经验和更高的亲社会性使得他们更善于根据他人反馈及时调整自己的行为 (Rosi et al., 2019)，可能表现出更高的互动质量水平。

This study employed a modified cooperative button-pressing paradigm (Cui et al., 2012; Miller et al., 2019; Yang et al., 2023), in which two participants needed to coordinate to press keys as synchronously as possible: the closer their button-press times, the better the cooperative performance. This paradigm is commonly used to investigate cooperative behavior, with the advantage that participants receive feedback about the relative timing of their button presses after each trial, allowing interaction partners to adjust subsequent pressing rhythms accordingly. Trial-based quantified behavioral data can be further associated with neural activity metrics, providing possibilities for understanding the neural basis of cooperative behavior. Functional near-infrared spectroscopy hyperscanning (fNIRS hyperscanning) allows researchers to investigate inter-individual neural synchronization and interaction patterns in natural social interaction contexts, making it suitable for exploring cooperative behavior and its neural mechanisms. Additionally, fNIRS hyperscanning has relatively high tolerance for head motion and, while maintaining temporal and spatial resolution, offers advantages for data collection with older adults. Furthermore, to examine individual personality trait similarity, we included the Big Five Personality Inventory to measure personality traits in both older and young adults.

Building on previous cooperation research, this study focused on three issues. First, previous cooperation studies have mainly concentrated on young populations (Romano et al., 2021), with nearly no discussion of cooperative behavior in older adults. However, as aging societies advance and social civilization develops, older adults are increasingly participating in social production activities, whether actively or passively. Therefore, investigating cooperative behavior in older adults has strong practical significance. Meanwhile, using fNIRS hyperscanning technology, this study examined the relationship between inter-brain activity synchrony and cooperative performance during cooperation. Inter-brain synchrony (IBS) is a neural marker of interaction quality (Cheng et al., 2015; Funane et al., 2011; Szymanski et al., 2017). Previous studies have shown significant IBS in the right superior frontal gyrus and right temporoparietal junction during cooperation (Cheng et al., 2015; Pan et al., 2017). Comparing cooperative behavior and neural activity differences between older and young adults helps us view cooperation from a developmental perspective and refine cooperation theories.

Second, by analyzing fNIRS neural activity and individual personality traits during the cooperative task, we attempted to explain the psycho-neural mechanisms underlying age differences in cooperative behavior. This study employed representational similarity analysis to calculate neural activity similarity during task completion and personality trait similarity between cooperating partners, and correlated these similarity matrices with the button-pressing behavior matrix. Social Identity Theory suggests that "more similar" individuals show better cooperative performance. This similarity may be based on appearance, personality traits, or immediate interaction experiences. Young and older adults may rely on different types of "similarity" during cooperation. Young adults are in a critical stage of self-concept and social identity development, so personality trait similarity may more strongly influence their cooperative performance. For example, previous research shows that individuals with similar personality traits, especially in agreeableness and extraversion, demonstrate better cooperation willingness in prisoner's dilemma games (Wilson et al., 2016). Personality similarity promotes shared understanding of situations, which may lead to more similar mental states and emotional responses, facilitating successful communication and cooperation (Matz et al., 2022). Compared to young adults, older adults have richer life experiences and higher socialization levels (Hess et al., 2005), and may rely less on personality trait similarity during cooperation, instead showing more prominent similarity in completing the interactive activity itself.

Finally, through Granger causality analysis, we can further clarify aging effects on information flow direction during cooperation. In cooperative processes, one party often assumes a dominant role while others tend to match this leader's behavior patterns and decisions (Calabrese et al., 2021; Nakayama et al., 2019). For example, in cooperative button-pressing tasks, faster-responding young participants often make compromises to achieve better cooperative outcomes, with information flow potentially moving from slow to fast responders (Wang et al., 2020). Older adults may focus more on common goals in cooperation and rely less on one party's leadership, with information flow more likely showing a bidirectional trend.

This study used a modified cooperative button-pressing paradigm with fNIRS hyperscanning and personality measurement to reveal changes in older adults' cooperative behavior and underlying neural mechanisms. Specifically, it tested three hypotheses: (1) Both older and young adults can demonstrate cooperative behavior in the button-pressing task, with cooperative behavior significantly positively correlated with IBS—higher IBS associated with smaller button-press time differences; (2) Regarding cooperation mechanisms, young adults' cooperative performance is more related to personality trait similarity, while older adults' performance is more related to neural similarity during task completion; (3) Age differences exist in information flow direction during cooperation: young adults may have a dominant party, while older adults may show bidirectional information flow without a clear leader.

Methods

2.1 Participants This study recruited 54 participants, including 30 young adults (age: 18-25 years, M = 21.40, SD = 1.82, 16 females) and 24 older adults (age: 58-75 years, M = 66.71, SD = 4.33, 16 females). They were randomly formed into 15 same-gender young dyads and 12 same-gender older dyads, with age differences within older dyads less than 10 years. fNIRS data from 2 young dyads were excluded due to equipment failure. All participants were right-handed, had normal or corrected-to-normal vision, normal color vision, and no history of psychiatric disorders or brain injury. All older adults completed the Mini-Mental State Examination (MMSE), with inclusion criteria of scores >24 and $ $6 years of education. Before the experiment, participants completed basic demographic information and a brief Big Five personality inventory (Thalmayer et al., 2011). All signed informed consent and were told that compensation (50-70 RMB) would be performance-based. The experiment was approved by the [MASKED] Ethics Committee (No. MASKED).

2.2 Cooperative Task Upon arrival, two participants were randomly numbered as Participant 1 and Participant 2, and the experimenter explained the task procedure and rules. Throughout the experiment, participants focused on the computer screen before them (Figure 1 [Figure 1: see original paper]C) and were prohibited from any verbal or non-verbal communication with their partner. To prevent observation of the partner's button-pressing actions, participants' hands were covered with a custom-made hollow box. The experimenter began the formal experiment after confirming understanding. Participants first rested calmly for 30 seconds, keeping relaxed and minimizing head movement. The task was programmed and presented using E-prime 3.0.

The cooperative button-pressing task procedure (Figure 1A) was as follows: A hollow gray circle remained on screen for 0.6-1.5 seconds, then rapidly changed from gray to green, prompting both participants to press keys quickly with their dominant hand. Participant 1 pressed "Z" and Participant 2 pressed "3". After pressing, 2-second feedback appeared. Participants were instructed to press simultaneously. To maintain attention and enhance cooperation, if the button-press delay was below a threshold (calculated as 1/8 of the dyad's average response time), both earned 1 point; otherwise, neither earned points, starting from 100 points. The 1/8 parameter was subjectively set to maintain moderate task difficulty. After the slower member pressed, the current trial result ("Win!" or "Fail!") and cumulative score were displayed for 2 seconds. Feedback also indicated which participant was faster (green "+") or slower (white "-"). After feedback, an inter-trial interval (black screen, 4 seconds) preceded the next trial. The task comprised two blocks of 20 trials each. Detailed procedures are available in previous literature (Cui et al., 2012). Before the formal experiment, participants completed 5 practice trials to ensure task comprehension.

Figure 1. Experimental procedure and fNIRS optode distribution. (A) Cooperative button-pressing task procedure. The task used a block design with 3 rest periods (30 seconds each) and 2 experimental blocks (20 trials each). (B) fNIRS optode arrangement. Using Fpz as reference, red indicates emitter optodes, blue indicates detector optodes, and numbers indicate corresponding channels. (C) Experimental scene photograph.

2.3 fNIRS Data Acquisition fNIRS hyperscanning offers high ecological validity and head motion tolerance, widely used in interactive behavior research in naturalistic settings. This study used a Shimadzu multi-channel desktop fNIRS system (FOIRE-3000, Shimadzu) to record cerebral blood oxygen signals during cooperative button-pressing, with a sampling rate of 7.69 Hz and wavelengths of 780 nm, 805 nm, and 830 nm. Using different absorption coefficients at these wavelengths, relative concentration changes in oxyhemoglobin (Oxy-Hb), deoxyhemoglobin (Deoxy-Hb), and total hemoglobin (Toxy-Hb) were detected. Cooperation is a high-level social cognitive function; following previous research, the prefrontal cortex (PFC) was set as the region of interest (Cheng et al., 2015; Cui et al., 2012). Each participant wore 16 optodes (8 emitters and 8 detectors alternately arranged) with 3 cm inter-optode distance, ensuring measurement of hemodynamic changes 2-3 cm deep in cortex, forming 22 channels (Figure 1B). According to the international 10-20 system, the middle optode of the lowest row aligned with Fpz, the optode cap bottom was placed above the eyebrows, and middle optodes were aligned along the sagittal reference curve above the nose to ensure accurate positioning.

2.4 Big Five Personality Measurement Personality traits were assessed using the Big Five Personality Inventory (Costa Jr & McCrae, 1992), a personality test based on the Five-Factor Model measuring openness, conscientiousness, extraversion, agreeableness, and neuroticism. This study used the brief version (Thalmayer et al., 2011) with 60 items (12 per dimension) using a 5-point scale from "very uncharacteristic" to "very characteristic," with some reverse-scored items. The scale showed good internal consistency reliability (Cronbach's α = 0.78).

2.5 Data Analysis

2.5.1 Behavioral Data In the cooperative button-pressing paradigm, dyadic cooperative performance was defined as the absolute difference between two participants' reaction times (Cooperative Performance = $|RT_1 - RT_2|$). Smaller differences indicated better cooperation. Considering that older adults have longer absolute RTs (Richer et al., 2018), which would inflate difference scores, we additionally defined corrected cooperative performance as the absolute RT difference divided by the sum of RTs (Corrected Cooperative Performance = $|RT_1 - RT_2| / (RT_1 + RT_2)$). Due to potential lapses in attention, outliers exceeding $±$3 SD from each subject's mean RT were removed (Li et al., 2022; Pan et al., 2017). A two-way mixed-design ANOVA was used with age (older vs. young) as between-subject factor and block (Block 1 vs. Block 2) as within-subject factor, with cooperative performance as the dependent variable.

2.5.2 fNIRS Data **Preprocessing:** The modified Beer-Lambert law was used to convert raw light intensity data into hemoglobin concentration data (Arridge et al., 1992; Delpy et al., 1988; Scholkmann et al., 2014). Numerous studies show that Oxy-Hb signals are more sensitive to cerebral blood flow changes and have higher signal-to-noise ratio than deoxyhemoglobin signals (Hoshi, 2003); therefore, only Oxy-Hb concentration signals were analyzed. For preprocessing, polynomial regression models estimated linear/non-linear trends, which were subtracted from raw hemoglobin signals to remove baseline drift; correlation-based signal improvement (CBSI) was used for motion correction to reduce artifacts from head movement (Vanutelli et al., 2016).

Inter-brain Synchrony Analysis: Wavelet Transform Coherence (WTC) was used to calculate inter-brain synchrony between corresponding channels of dyad partners. WTC calculates cross-correlation between two non-stationary time series (Grinsted et al., 2004), expressed as:

$$WTC_{m,s}(t,f) = \frac{|S(f^{-1}W_m(t,f)W_s^*(t,f))|^2}{S(f^{-1}|W_m(t,f)|^2) \cdot S(f^{-1}|W_s(t,f)|^2)}$$

where m and s represent the two time series signals. Higher WTC values indicate greater coherence between time series. By calculating WTC values for dyads' hemodynamic signals, inter-brain activity synchrony (IBS) can be measured.

Frequency Selection: WTC values from task and rest phases were compared across all frequencies using paired t-tests on Fisher-z transformed values to identify task-related frequencies as Frequencies of Interest (FOI). Overall IBS was defined as the average task IBS across both blocks minus inter-block rest IBS, Fisher-z transformed. The FOI in this study was 0.18-0.25 Hz.

Single-brain Activation Analysis: To identify brain activity related to cooperative button-pressing, channel-wise Generalized Linear Models (GLM) were conducted. During cooperation, participants predicted their partner's button press at each trial onset, with 2-second intervals between trials. This temporal information was used to construct the task design matrix, convolved with a standard Hemodynamic Response Function (HRF) and correlated with preprocessed HbO signals. Higher β values in the GLM indicated stronger task-HbO signal relationships. At the group level, paired t-tests compared β values during button-pressing and inter-trial intervals across all subjects and channels to identify channels significantly related to cooperative button-pressing as Regions of Interest (ROI) for subsequent RSA. FDR correction controlled for multiple comparisons ($p < 0.05$).

Representational Similarity Analysis: Inter-subject representational similarity analysis (IS-RSA) captures subtle differences and changes in brain and behavior while enriching information (Finn et al., 2020; Zhou et al., 2023). We used IS-RSA to analyze representational similarities among neural signals, behavior, and personality traits to examine relationships between cooperative behavior and neural/personality factors. First, Euclidean distances were calculated for differences in button-press RTs and Big Five dimension scores between each dyad to construct behavioral and personality dissimilarity matrices. Second, preprocessed HbO signals underwent Fast Fourier Transform to obtain power spectra. The square root of power spectra was calculated as signal fluctuation amplitude, averaged across 0.01-0.5 Hz. Neural dissimilarity matrices were built by calculating Euclidean distances between dyads' average amplitude fluctuations (Zhang et al., 2023b). All dissimilarity matrices were converted to similarity matrices by: Similarity = 1 - (d/d_{max}), where d is the distance and d_{max} is the matrix maximum. Spearman correlations between similarity matrices measured their associations. Permutation tests determined significance: rows and columns of the behavioral similarity matrix were randomly shuffled 5000 times to generate a null distribution, with the true correlation coefficient compared against this distribution.

Granger Causality Analysis: To analyze whether one participant dominated the cooperative task, Granger Causality Analysis (GCA) measured directional coupling between partners' brain signals. The faster responder with more trials was defined as the fast responder, and the other as the slow responder (Wang et al., 2020). GCA identifies coupling directionality by incorporating precedent information from one participant's fNIRS time series j(t) into a univariate autoregressive model for the other participant's time series i(t). The bivariate autoregressive model for time series i(t) is (Niso et al., 2013):

$$i(t) = \sum_{k=1}^{p} a_k i(t-k) + \sum_{k=1}^{p} b_k j(t-k) + \epsilon(t)$$

The Hermes toolbox for Matlab calculated Granger causality from fast-to-slow and slow-to-fast responders. One-sample t-tests examined whether each direction's Granger causality values differed from zero, and two-sample t-tests compared differences between directions within each age group.

Figure 2 [Figure 2: see original paper]. Data analysis pipeline.

Results

3.1 Behavioral Results A 2$×$2 repeated-measures ANOVA examined whether cooperative performance was affected by age and time course (Figure 3 [Figure 3: see original paper]). Results showed a significant Age × Block interaction (F(1, 25) = 12.28, p = 0.002, p^2 = 0.33). Simple effects revealed significant age differences in Block 1 (t(25) = 2.81, p = 0.009, Cohen's d = 1.94) but not in Block 2 (t(25) = 0.99, p = 0.219, Cohen's d = 0.53), as shown in Figure 3A. Additionally, significant main effects emerged for Age (F(1, 25) = 4.45, p = 0.045, p^2 = 0.15), with young adults outperforming older adults, and Block (F(1, 25) = 24.29, p < 0.001, p^2 = 0.49), with Block 2 outperforming Block 1. Figure 3B illustrates cooperative performance changes across interaction trials. The black dashed line shows a trendline fitted using Generalized Additive Models (GAM). Overall, older adults' cooperative performance improved with increasing trials, while young adults' performance remained stable. Using corrected behavioral data (accounting for initial button-press speed) yielded consistent results.

Figure 3. Cooperative behavior results. (A) Repeated-measures ANOVA results. (B) Cooperative performance changes across trials. The black dashed line represents the fitted trendline for cooperative performance changes, with error bars indicating 95% confidence intervals of sample means. *p < 0.05, **p < 0.01.

3.2 Inter-brain Synchrony During cooperative button-pressing, older adults showed significant IBS in prefrontal channels 2, 6, 11, 14, 15, 17, and 21 (Figure 4 [Figure 4: see original paper]A). Young adults showed significant IBS in channels 1, 4, 5, 6, 12, and 22 (Figure 4B). Both age groups showed right prefrontal IBS, with both groups showing significant IBS in channel 6, corresponding to the right superior frontal gyrus (rSFC). Two-sample t-tests on IBS revealed a marginally significant group difference in channel 6 ($t(23) = 2.00$, $p = 0.058$). Moreover, IBS in this channel significantly negatively correlated with cooperative performance improvement ($r = -0.57$, $p = 0.003$), indicating that greater IBS increases were associated with larger performance improvements (Figure 4C).

Figure 4. Inter-brain synchrony results. (A) t-value distribution of IBS in older adults during cooperative button-pressing. (B) t-value distribution of IBS in young adults. (C) t-value map of age group differences in IBS, with trending differences concentrated in right frontal regions. Channel 6 (corresponding to right superior frontal cortex in the ALL template) showed marginally significant IBS differences between groups, and IBS change values in this channel significantly negatively correlated with cooperative performance change values.

3.3 General Linear Model Analysis GLM β values were calculated for each trial's task and interval periods. Group-level paired t-tests comparing task vs. interval β values showed significant differences in channels 1 (rMFC, $t(49) = 3.53$, FDR $p < 0.001$), 5 (rMFC, $t(49) = 3.00$, FDR $p = 0.004$), 6 (rSFC, $t(49) = 2.37$, FDR $p = 0.022$), 10 (rMFC, $t(49) = 2.52$, FDR $p = 0.015$), 11 (rSFC, $t(49) = 2.23$, FDR $p = 0.031$), 16 (SFC, $t(49) = 3.25$, FDR $p = 0.002$), and 20 (rFPC, $t(49) = 2.47$, FDR $p = 0.020$) (Figure 5 [Figure 5: see original paper]B). These results indicate that HbO signals in rMFC and rSFC were more closely related to the cooperative task, and these channels were selected as ROIs for subsequent RSA.

Figure 5. General linear model results. (A) Preprocessed Oxy-Hb concentration changes for a single subject across task progression, with gray dashed lines indicating trial onsets. (B) Group-level t-test results for GLM β values (FDR corrected, $p < 0.05$). Brain regions associated with cooperative task were mainly concentrated in right frontal cortex.

3.4 Representational Similarity Analysis To further clarify age differences in neural signals, personality traits, and cooperative performance, we conducted RSA among the three factors (Figure 6 [Figure 6: see original paper]). RSA between behavioral and neural matrices showed significant Spearman r values in older adults for channels 1, 6, 10, and 11 ($ps < 0.05$), while young adults showed significance only in channel 6 ($p = 0.028$). Furthermore, the channel 6 r value differed significantly between older and young groups ($Z = 5.03$, $p < 0.001$), with older adults showing significantly stronger neural-behavior associations.

RSA between behavior and personality showed non-significant Spearman r in older adults ($r = 0.06$, $p = 0.273$), suggesting their cooperative behavior may be independent of personality traits. In young adults, behavior-personality matrix Spearman r was significant after 5000 permutations ($r = 0.21$, $p = 0.008$). We further examined whether personality similarity between partners affected cooperative performance by calculating the inverse of Euclidean distance between partners' personality scores (1/d) as a similarity index and correlating it with average cooperative performance across all trials. Results showed no significant correlation in older adults ($r = -0.32$, $p = 0.318$), but a significant negative correlation in young adults ($r = -0.61$, $p = 0.026$), indicating that more similar personality traits predicted better cooperative performance in young adults.

Figure 6. Representational similarity analysis results. (A) Older adult RSA. Behavioral, neural, and personality matrices were constructed from inter-subject Euclidean distances of corresponding measures. Spearman correlation coefficients between behavioral and neural matrices are shown as r-value heatmaps on the left cortical surface, with permutation-tested r values and significance for ROI channels shown in bar charts below. Behavior-personality matrix permutation correlation was non-significant; Pearson correlation between personality similarity and cooperative performance was non-significant. (B) Young adult RSA. Matrix calculation and heatmap construction followed the older adult procedure. r-value heatmaps and bar charts follow the same format as panel A. Behavior-personality matrix permutation correlation was significant. Pearson correlation between personality similarity and cooperative performance was significantly negative, indicating better cooperation with greater personality similarity. *$p < 0.05$,* ***$p < 0.01$,*** $p < 0.001$, ns = non-significant.

3.5 Directionality of Inter-brain Synchrony One-sample t-tests examined whether Granger causality values in each direction significantly exceeded zero for each age group. Results showed all four directions were significantly >0 in channel 11: older slow→fast ($t(11) = 7.40$, $p < 0.001$, Cohen's $d = 0.05$), older fast→slow ($t(11) = 4.34$, $p = 0.001$, Cohen's $d = 0.04$), young slow→fast ($t(12) = 8.75$, $p < 0.001$, Cohen's $d = 0.04$), and young fast→slow ($t(12) = 6.74$, $p < 0.001$, Cohen's $d = 0.02$). Two-sample t-tests comparing directions within each age group (Figure 7 [Figure 7: see original paper]) revealed significant directionality differences in young adults ($t(24) = 2.87$, $p = 0.008$, Cohen's $d = 0.02$), with slow→fast brain signal directionality significantly higher than fast→slow. No significant directionality difference emerged in older adults ($t(22) = 0.31$, $p = 0.760$).

Figure 7. Granger causality analysis results. The faster, more frequent responder in the cooperative task was defined as the fast responder, and the other as the slow responder. Two-sample t-tests on slow→fast and fast→slow Granger causality values for each age group showed young adults exhibited slow→fast brain coupling directionality in channel 11, while older adults showed no significant directionality. **$p < 0.01$, ns = non-significant.

Discussion

Whether older adults can achieve the same cooperative performance as young adults despite cognitive decline and crystallized self-concept is a question with strong practical significance amid severe global aging and labor contraction. Examining age differences in cooperative behavior and neural activity provides a developmental perspective for deepening our understanding of cooperation mechanisms and refining cooperation theories. Using a modified button-pressing cooperation task combined with fNIRS hyperscanning and personality measurement, this study explored age differences in cooperative behavior and underlying dual-brain neural foundations. Results showed older adults achieved cooperative performance comparable to young adults. Inter-brain synchrony was significantly correlated with cooperative performance, with higher IBS associated with smaller button-press time differences. Moreover, psycho-neural mechanisms differed between age groups: young adults' cooperation was more related to personality similarity, while older adults' cooperation depended more on neural similarity during task completion. Granger causality analysis suggested young adults had a leader in cooperation, whereas older adults showed bidirectional information flow.

Regarding behavioral performance, both block-wise (Block 1 vs. Block 2) and trial-by-trial results showed older adults eventually reached the same cooperation level as young adults, though this was modulated by task time course (Figure 3). Initially, older adults' cooperative performance was significantly lower than young adults', but with increasing interaction trials, the performance gap gradually diminished until reaching equivalent levels. These results indicate that, on one hand, older adults can achieve young adult-level cooperation through learning and mutual adaptation; on the other hand, young adults' cooperation was unaffected by time course, possibly because the button-pressing task was relatively simple for them, with partners' presses being close from the initial stage. Similar findings appear in related research, where young adults' cooperative performance shows no significant improvement across trials (Liu et al., 2024). fNIRS hyperscanning results showed that both single-brain activation and IBS during cooperation were mainly concentrated in right frontal regions, consistent with previous cooperation studies (Cheng et al., 2015; Cui et al., 2012). Compared to young adults, older adults activated broader brain regions and showed higher IBS during cooperation. Increased IBS is typically associated with interaction quality. As a neural marker, older adults' stronger IBS may reflect more effective interaction mobilization during task completion. However, similar to behavioral performance, young adults' lower IBS may be because task difficulty was relatively simple for them, allowing high cooperation levels without recruiting relevant brain regions.

Representational similarity analysis further explored age differences in cooperation mechanisms, revealing that older adults relied more on task-related neural activity, while young adults' cooperation was more associated with personality similarity. Neural RSA showed that compared to young adults, older adults had broader prefrontal cortex regions related to cooperative task (channels 1, 6, 10, 11, involving right superior frontal gyrus rSFC and right middle frontal gyrus rMFC), while young adults showed significant behavior-neural representation correlation only in channel 6 (rSFC). Even for channel 6, older adults' representational similarity correlation coefficient was significantly higher than young adults'. These findings suggest older adults' cooperation may depend more on the task itself. Of course, this could also be because the task was simple for young adults but relatively difficult for older adults, requiring older adults to "mobilize" more prefrontal cognitive resources for compensation (Morcom & Henson, 2018). For instance, research examining age differences in adolescent and adult cooperation found that adolescents also needed to recruit more cognitive resources to maintain adult-level cooperation (Yang et al., 2023). On the other hand, cooperation research shows personality similarity importantly influences cooperation willingness and performance, with individuals tending to cooperate with similar others (Traulsen, 2008). This study found similar results: young dyads with higher personality similarity showed better cooperative performance, while this effect was absent in older dyads. This confirms Social Identity Theory's hypothesis that young adults are more inclined to establish connections and understanding with similar individuals to build social identity, with cooperative performance significantly correlated with personality similarity. With age, older adults' life experiences and life-cycle transitions have established relatively stable social identity, making their cooperative performance less affected by partner similarity. These results suggest older adults' cooperative abilities may be more socially identity-inclusive, enabling cooperation with diverse individuals.

To further clarify information flow direction during cooperation, we conducted Granger causality analysis. Results showed young adults had a "leader" in cooperation, specifically with slower responders guiding faster responders' button-pressing, or faster responders receiving information from slower responders to adjust speed. Young adults have strong cognitive control abilities, including response speed and executive functions. Therefore, in cooperative tasks, faster young partners may predict slower partners' next button press and adjust their own timing to optimize cooperative performance, showing brain coupling direction from slower "followers" to faster "leaders"—fast responders receive information from slow responders to adjust behavior. Similar results appear in romantic partners' cooperative button-pressing tasks, where despite men's faster responses, information flow is from women to men (Griskevicius et al., 2006; Pan et al., 2017). Older adults showed no "leader" during cooperative button-pressing, with information flow showing bidirectional trends, indicating that response speed does not determine information flow direction in older adults' interactions.

This study has several limitations. First, cooperation involves predicting others' intentions, and the right temporoparietal junction is a crucial brain region for theory-of-mind processing. Limited by equipment optode number, our hyperscanning focused on partners' prefrontal cortex. Future research could simultaneously collect brain signals from both prefrontal cortex and right temporoparietal junction for functional connectivity (Liu et al., 2024) and hyperbrain network analysis (Wang et al., 2022). Second, using response speed for Granger causality analysis resulted in unbalanced trial numbers: some dyads had "fast responders" who were faster in all trials, while others had fast and slow responders with similar numbers of faster trials (Wang et al., 2020). Future studies could directly design cooperative tasks with role differentiation as a manipulated variable. Third, although the cooperative button-pressing task is a classic paradigm for studying cooperation and we used hyperscanning to simultaneously collect both partners' neural activity, future research could further improve ecological validity by considering verbal or non-verbal communication during cooperation.

This study used a cooperative button-pressing paradigm and hyperscanning technology to investigate aging effects on cooperative behavior and its dual-brain basis. Behavioral and IBS results suggest older adults have cooperative levels comparable to young adults. Moreover, correlation analyses of cooperative behavior with neural and personality representational similarities revealed that young adults' cooperation was influenced by personality similarity, while older adults depended more on neural activity similarity during task completion. These findings reflect that compared to young adults, older adults may be less concerned with "who" their partner is and more focused on the task itself. The results demonstrate that older adults can achieve young adult-level cooperation through multi-trial practice, can still participate in social development involving cooperation after entering older age, and can contribute to maintaining the demographic dividend.

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