Friendship modulates physical effort and neural dynamics during group coordination in shared social networks

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ABSTRACT

Human social interactions are embedded within social networks, yet it remains unclear how existing interpersonal relationships influence the behavioural and neural dynamics of collective action. Here, we combined social network mapping with three-person EEG-hyperscanning to investigate how friendships within shared networks modulate effort allocation during real-time coordination. We mapped social networks across seven undergraduate cohorts and recruited triads composed of two mutually close friends and one non-friend from the same network. Triads performed a novel joint motor task in which they produced forces towards a collective target. Non-friends consistently produced greater and more vigorous forces than friends during joint action, an effect strongest among non-friends embedded in smaller social networks. Non-friends also exhibited stronger alpha- and beta-band event-related desynchronization, inter-subject correlation, and inter-brain group phase synchrony, consistent with greater engagement of action-related and attentional processes. Taken together, these findings show that friendship and social network context influence how individuals allocate physical effort and engage during coordination, suggesting that non-friends invest more effort and attention when interacting in socially asymmetric group settings. By linking real-world friendships to behavioural and multi-brain neural dynamics, this work demonstrates that relational context within social networks is embodied in the mechanisms supporting human group coordination.

***Keywords*:** Friendship, social networks, group coordination, joint action, EEG hyperscanning

1 Introduction

Friendship is one of the most powerful social ties humans form, shaping well-being, identity, and opportunities across the lifespan (Hartup and Stevens, 1997; van der Horst and Coffé, 2012; Dunbar, 2018; Alsarrani et al., 2022; Pezirkianidis et al., 2023). It forms the foundation of our social networks, which provide the broader societal context within which close relationships emerge and evolve. Yet despite its prominent role in social life, we know remarkably little about how friendship influences real-time moment-to-moment processes through which people interact and coordinate with one another.

Understanding this influence is crucial because coordination underlies many everyday behaviours - from moving furniture and cooking together, to group decision making at work and team sports. Such coordinated actions rely not only on cognitive mechanisms, such as integration of sensory information from one's own and others' actions, anticipation and adaptation to others' behaviour, and real-time allocation of effort (Sebanz et al., 2006; Knoblich et al., 2011; Vesper et al., 2017; Sebanz and Knoblich, 2021), but also on the relational context in which coordination unfolds (Tomasello, 2014; Clark-Polner and Clark, 2014; Chierchia et al., 2020). Social familiarity, prior interaction history, and broader network structure can influence people's sensitivity to social interactions (Baek et al., 2025), how much they cooperate or adapt their behaviour to each other (Pan et al., 2017; Speer et al., 2024), and in turn how effort is distributed across group members (Karau and Williams, 1993). This raises the question of how friendship and social network position modulate real-time behavioural and neural coordination dynamics, par-

ticularly in interactions involving more than two people from shared social networks.

Competing predictions can be made regarding how friendship influences effort allocation during collective action. On the one hand, close relationships and social familiarity may promote prosocial motivation, trust, and commitment to collective outcomes (Larzelere and Huston, 1980; Rempel et al., 1985; Karau and Williams, 1993; Van Lange et al., 1997; Wieselquist et al., 1999; Alarcon et al., 2016; Chierchia et al., 2020). From this perspective, friends may be expected to contribute more effort during coordination, reflecting greater concern for shared success or willingness to support one another. On the other hand, interactions with non-friends may heighten arousal, uncertainty of one's role within the group, and sensitivity to evaluation (Cottrell and Neuberg, 2005; Holt-Lunstad et al., 2007; Pardede and Kovač, 2025), as well as motivation to signal competence or value to the group in order to belong (Zajonc, 1965; Tetlock and Manstead, 1985; Leary and Kowalski, 1990; Williams and Karau, 1991; Baumeister and Leary, 1995; Maner et al., 2007; Karau and Wilhau, 2020). In this case, non-friends may contribute more effort during joint tasks, particularly when their role or standing within the group is uncertain.

Distinguishing between these possibilities requires methods that measure both how groups coordinate actions together and the neural mechanisms that are engaged during real-time interaction. Recent advances in social neuroscience and joint action have highlighted the need for interactive paradigms and multi-person neuroimaging for studying such processes (De Jaegher et al., 2010; Dumas, 2011; Konvalinka and Roepstorff, 2012; Schilbach et al., 2013; Dingemanse et al., 2023). Dyadic joint action studies show that successful coordination relies on real-time prediction of others' movements, the ability to generate predictable actions oneself particularly when sensory access to partners is limited, and continuous mutual adaptation that allows individuals to maintain temporal alignment (Knoblich and Jordan, 2003; Keller et al., 2007; Konvalinka et al., 2010; Noy et al., 2011; Vesper et al., 2011; Pecenka and Keller, 2011; Keller et al., 2014; Vesper et al., 2017; Pezzulo et al., 2019; Konvalinka et al., 2023b). The neural mechanisms supporting these processes are more poorly understood, but interactive EEG studies demonstrate that sensorimotor coupling during coordination is accompanied by enhanced mu-, alpha- and beta-band desynchronization (Tognoli et al., 2007; Perry et al., 2011; Dumas et al., 2012; Naeem et al., 2012; Konvalinka et al., 2014; Zamm et al., 2021; Zimmermann et al., 2022; Flösch et al., 2023), consistent with mechanisms of action preparation and execution, motor prediction, and increased attentional allocation to others' behaviour.

Multi-brain approaches have shown that people also synchronize neural rhythms with each other during action coordination (Dumas et al., 2010; Müller et al., 2013; Zamm et al., 2018; Fishburn et al., 2018; Gugnowska et al., 2022). Beyond oscillatory markers, inter-subject correlation (ISC) methods have shown that when people attend to the same visual or auditory stimulus, even in the absence of interaction, their neural signals become correlated as a result of common stimulus locking (Dmochowski et al., 2012; Cohen and Parra, 2016; Nastase et al., 2019; Madsen and Parra, 2022). Building on this principle, correlated components analysis (CorrCA) extracts shared neural components that are maximally aligned across individuals viewing or listening to a common stimulus (Parra et al., 2019). ISC has been shown to increase during periods of joint attention, and decrease with distraction (Golland et al., 2015; Pérez et al., 2021). It has thus been purposed to serve as a marker of joint attentional engagement, with higher correlation reflecting more consistent, time-locked processing of the task across individuals (Hasson et al., 2004; Dmochowski et al., 2012, 2014; Cohen et al., 2018; Nastase et al., 2019; Rai et al., 2025; He et al., 2025).

Despite this progress, relational context has rarely been incorporated into interactive neuroscience paradigms (Clark-Polner and Clark, 2014), as most joint action studies recruit strangers or pair participants with confederates, leaving open how naturally occurring social relationships influence coordination and underlying neural processes (Clark-Polner and Clark, 2014). Recent work in social network neuroscience has shown that people neurally encode properties of their social networks (Schmälzle et al., 2017; Baek et al., 2023; Sijtsma et al., 2023; Baek et al., 2025), and that friends have neuroanatomically more similar brains (D'Onofrio et al., 2022), and exhibit more similar neural responses at rest (Hyon et al., 2020b) and during passive video watching tasks (Parkinson et al., 2018; Hyon et al., 2020a; Shen et al., 2025). A small number of interactive studies have begun to investigate

how social network properties and relational context influence face-to-face interaction dynamics. This work shows that network centrality modulates how strongly people influence or are influenced by others in consensus-building conversations (Sievers et al., 2024). In addition, friendship status affects linguistic and neural convergence during conversation, with strangers showing greater convergence and reduced exploratory behaviour compared to friends (Speer et al., 2024). Together, these findings highlight the role of friendship and social network properties in modulating how people perceive, adapt to, and interact with one another. Yet it remains unclear how asymmetric social relationships and network properties embedded within the same group influence the moment-to-moment collective coordination dynamics and their underlying neural mechanisms.

Here we address this question by combining social network mapping with three-person EEG-hyperscanning to investigate how friendship dynamics within shared social networks influence physical effort allocation and neural engagement during group coordination. We mapped social networks across seven bachelor program study lines (Figure 1A), and recruited triads composed of two mutually close friends and one non-friend from the same study line networks. The triads engaged in a novel three-person coordination task (Figure 1B) - the "Force Game" - in which they jointly coordinated their force contributions to reach specific target forces by applying pressure to individual pressure measuring devices, while receiving continuous or non-continuous visual feedback of joint, but not individual, contributions (Figure 1). This design allowed us to test the two competing hypotheses: whether friends contribute more physical effort, by allocating more attention and hence commitment to the joint task; or whether non-friends contribute more physical effort, due to heightened engagement, potentially driven by their evaluation sensitivity or uncertainty about their role in the group. We show that non-friends consistently contributed greater physical force and produced force more vigorously than friends during joint tasks. This effect was strongest for non-friends from smaller class social networks, indicating that individuals within smaller networks may be more sensitive to how they are perceived by their familiar but non-friend peers. Non-friends also exhibited greater alpha and beta event-related desynchronization, higher neural inter-subject correlations, and stronger neural group phase synchrony, suggesting increased attention and engagement during the task. By combining relative friendship information from shared social networks, real-time behavioural coordination paradigms, and multi-brain imaging, we provide evidence that asymmetric social relationships are embodied in the motor and cognitive processes that support human group coordination.

2 Results

2.1 Social network mapping

We first mapped the social networks of seven bachelor program study lines, with class sizes ranging from 43 to 184 students ($M = 83.14; SD = 44.26$). Students were asked to complete a questionnaire in which they checked off the individuals they considered to be friends or close friends (see Methods for definitions) from a roster of all of their classmates in the same study line. 378 students gave informed consent to have their social networks mapped across the seven social networks (Figure 1A), ranging from 28 to 113 ($M = 54.0; SD = 27.09$) students per study line class.

A subset of the students ($N = 93$) were recruited as triads, consisting of two mutually reported close friends and one non-friend (defined as mutual lack of social ties to the friend-pair), to participate in the Force Game experiment (Figure 1B). These participants filled out an additional friendship questionnaire, where they were asked to list their friends and close friends outside of the study line class social networks, to obtain a more complete estimate of the number of friends for each participant. Overall, the non-friends had significantly fewer friends (Supplementary Figure S1; FDR-corrected p-values for class close friends: $p < 0.01$; class friends $p < 0.05$; close friends and friends outside classroom $p < 0.05$).

2.2 Non-friends contribute greater and more vigorous forces compared to friends in group coordination

Participants were instructed to apply forces by pressing on individual pressure measuring devices in order to individually or jointly reach specific target forces visually shown on their individual screens at the start of each trial (Figure 1C), whilst three-person hyperscanning EEG was measured. Participants either performed the task alone (solo) or interactively. In interactive trials, they had to reach the target force together in

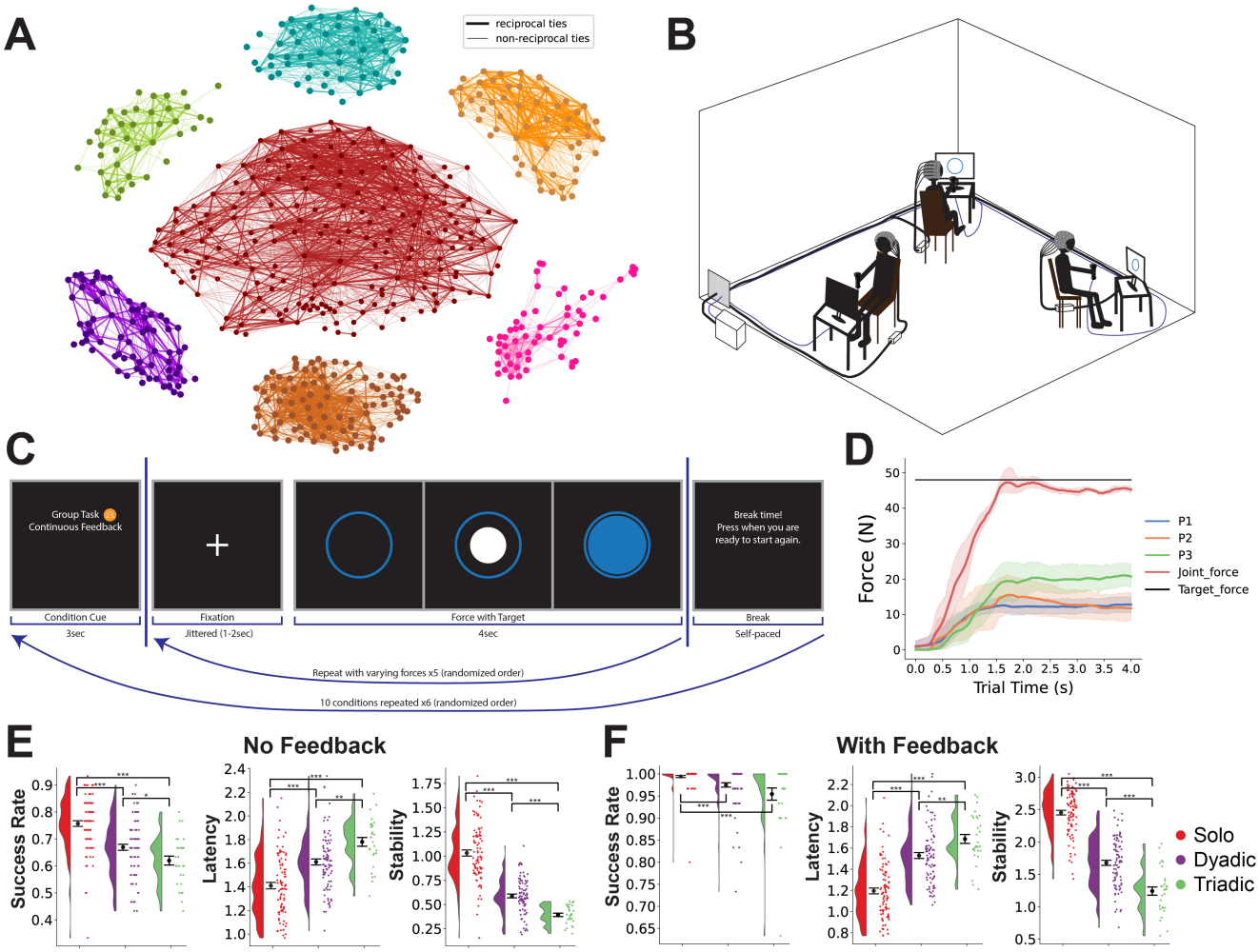

Fig. 1. **Schematic of the Force Game setup.** A) Social networks of seven bachelor program study lines were mapped. B) Triads, consisting of two close friends and one non-friend from the same study line, performed the Force Game together. C) Timeline of the experimental paradigm for a single trial. The blue circle indicates the target force, and filled circles indicate the joint force produced, in a continuous visual feedback trial. The blue arrows beneath the timeline indicate the repeated loops corresponding to different force levels and conditions. D) Example of the averaged forces across the 4-second triadic trials with continuous visual feedback from one triad. E-F) Behavioural performance, estimated with success rate, latency and stability around the target force, for trials E) without continuous visual feedback and F) with continuous feedback.

triads (referred to as triadic trials), or in dyads where one person's device did not contribute to the total force (dyadic trials), a manipulation they were not aware of. Additionally, we manipulated whether the interaction recruited adaptive or predictive mechanisms, by either giving continuous visual feedback - displayed as a filled circle on the screen - or no feedback across the 4-second trial followed by discrete feedback of the reached force at the end of the trial. The feedback given in interactive trials was always of the joint force, hence individual forces had to be inferred. The participants were thus not given feedback of their relative contributions. Each condition was repeated 30 times with varying target forces, represented by the radius of the target circle. An example of the trial averaged produced forces across the 4-second interaction from one triad can be seen in Figure 1D, depicting group interaction with continuous feedback.

To validate the Force Game paradigm, we estimated how well the participants performed the task. As expected, participants performed better with continuous visual feedback and performance deteriorated as more people contributed, i.e.,

with the best performance observed in solo trials, and worst in triadic ones (Figure 1E-F), likely reflecting greater perceptual demands placed on each participant when integrating the collective joint force.

To test whether different coordination mechanisms emerged between friends and non-friends, we first investigated how much force each participant contributed to the joint task. Here, a systematic asymmetry emerged: non-friends contributed greater physical force than friends (Figure 2), during both dyadic and triadic coordination, and both in interactions with (FDR-corrected $p < 0.05$) and without continuous visual feedback (FDR-corrected $p < 0.01$).

To unpack how this asymmetry unfolded over time, we next performed a more temporally fine-grained analysis of the force dynamics, to better characterize the social timing during the task (Konvalinka et al., 2023a). Specifically, we estimated the first derivative of the behavioural force time series, commonly known as rate of force development (RFD) (Maffiuletti et al., 2016)), for each trial (Supplementary Figure S2). The peak RFD was then averaged over trials (Figure 3), as a proxy of movement vigour (Marinovic et al., 2017). Non-friends had higher peak RFD in interactive dyadic and triadic trials with and without continuous visual feedback (FDR-corrected $p < 0.05$), while no effect of friendship on peak RFD was observed in solo trials. This indicates that non-friends produced more vigorous movements, specifically during the group coordination tasks.

We did not find differences in overall performance between friends and non-friends. Friends and non-friends performed equally well in solo tasks (Supplementary Figure S3), and performance in dyadic friend – friend interactions was also on par with friend – non-friend interactions (Supplementary Figure S4).

2.3 Force asymmetry was primarily observed in smaller study line classes

We hypothesized that the force asymmetry between friends and non-friends may be explained by social disparity, and that non-friends from smaller classes or with fewer friends may feel more of a need to belong (Baumeister and Leary, 1995), or be more sensitive to how they are perceived, hence contributing more force. Thus we investigated the effect of study line class size and number of friends on the relative amount of force produced.

Strikingly, a clear association between the size of the study line classes and amount of relative force was observed, with greater force asymmetry observed in smaller classes. Non-friends from smaller classes contributed more force, which was negatively correlated with class size, such that the smaller the class size the non-friends came from the more force they contributed relative to the friends. This effect was significant for both dyadic and triadic interactions with continuous visual feedback (Figure 4; FDR corrected p-values for Dyadic: Friends $p = 0.003$, Non-friend $p = 0.002$; Triadic: Friends $p = 0.09$, Non-friend $p = 0.001$). While the same trend was observed for interactions without continuous feedback, the association was not significant. Similar negative correlations in non-friends were observed when correlating RFD with class sizes, although the correlations did not survive multiple test correction (Supplementary Figure S5; lowest uncorrected p-values for non-friends with continuous visual feedback: $p = 0.038$; no feedback: $p = 0.096$; lowest FDR corrected p-values with and without feedback: $p = 0.14$).

We hypothesized that non-friend participants with fewer friends overall may be more likely to contribute more force to the interaction relative to the two friends. We indeed observed a negative trend between the number of close friends outside the class social network and relative force in trials without continuous feedback for non-friends; however, this effect did not survive multiple test correction (Supplementary Figure S6; uncorrected p-values for non-friends in Dyadic interactions: $p = 0.02$, Triadic: $p = 0.01$; FDR corrected p-values for Dyadic and Triadic: $p = 0.17$).

2.4 Non-friends exhibit increased alpha and beta event-related desynchronization

To investigate the neural mechanisms underlying social coordination, we analysed evoked alpha and beta event-related synchronization, EEG markers of sensorimotor prediction, preparation, execution, and attention. The Force Game was designed with 30 repeated trials for each condition, which enabled us to increase the signal-to-noise ratio by averaging over trials to perform event-related power analysis across classical EEG frequency bands (Supplementary Figure S7).

Across all conditions, we observed the expected sensorimotor alpha and beta event-related desynchronization (ERD) over left-hemispheric central electrodes contralateral to the

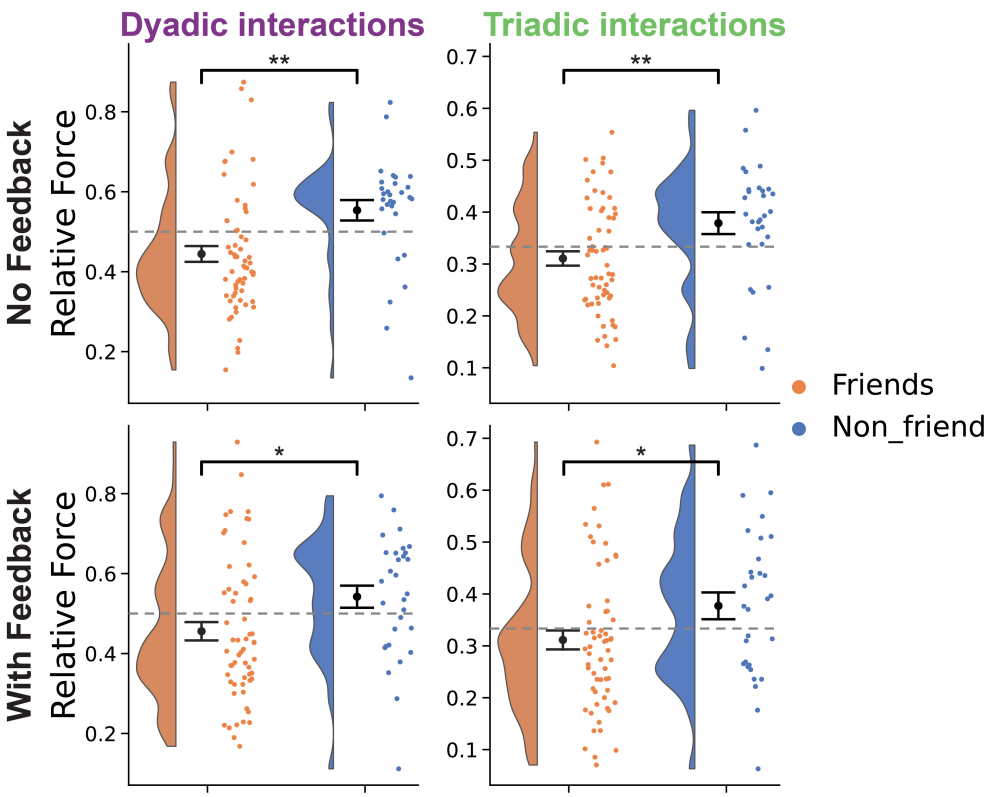

Fig. 2. **Non-friends produced greater physical force as compared to friends.** Non-friends contributed greater physical force to reach the targets in both the dyadic and triadic joint tasks, with and without continuous visual feedback. The striped line corresponds to equal force contribution from all participants during a trial. $^{*}p < 0.05$, $^{**}p < 0.01$. P-values were derived using non-parametric permutation tests with FDR multiple test correction.

moving hand, with desynchronization occurring shortly after the onset of the visual stimulus (the appearance of the target force) (Figure 5A). This pattern is consistent with classical findings linking alpha and beta desynchronization to motor preparation and execution during voluntary movement (Salmelin and Hari, 1994; Pfurtscheller and Lopes da Silva, 1999; Fujioka et al., 2012; Ross et al., 2017; Zamm et al., 2021).

We tested whether these neural responses differed as a function of friendship, i.e., whether non-friends exhibited larger desynchronization during interactive trials. When contrasting friends and non-friends, non-friends exhibited greater ERDs across all frequency bands, illustrated for alpha in Figure 5B. To account for multiple comparisons across time, space (electrodes), and frequency, we conducted non-parametric cluster-based permutation tests (Maris and Oostenveld, 2007; Pernet et al., 2015; Sassenhagen and Draschkow, 2019). In trials with continuous visual feedback, non-friends had significantly greater ERDs across solo ($p = 0.006$), dyadic ($p = 0.033$) and triadic ($p = 0.01$) conditions (Supplementary Figure S8D-F). The clusters consistently spanned approximately 1.1s to 1.7s post-stimulus onset and extended across delta, theta, alpha and beta frequency ranges, across frontal, lateral-central and posterior regions. No significant differences in ERDs were observed between friends and non-friends in trials without continuous visual feedback (Supplementary Figure S8A-C).

Alpha and beta oscillatory activity have been commonly linked to top-down modulation of sensorimotor processing and are thought to play an important role in regulating attention, as they are often modulated by task demand and cognitive effort (Klimesch, 1999; Pfurtscheller and Lopes da Silva, 1999; Mathewson et al., 2012; Keehn et al., 2017; Stecher et al., 2025). Consistent with this interpretation, we observed sustained alpha and beta ERD in trials with continuous visual feedback, whereas power rebounded toward the baseline

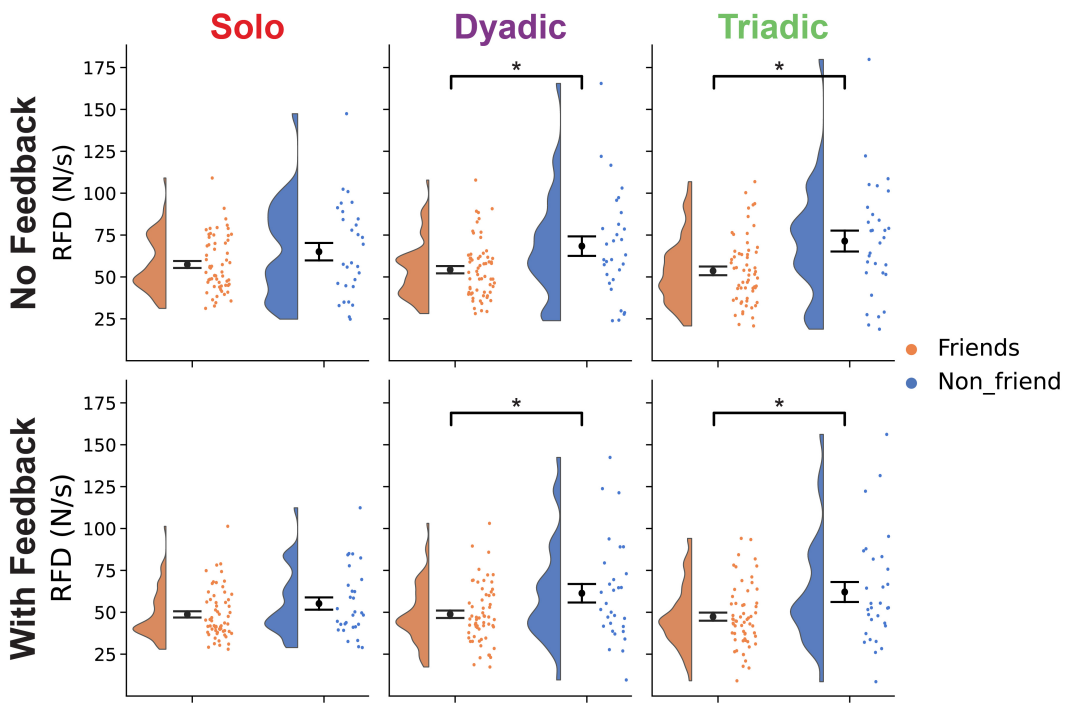

Fig. 3. **Non-friends produced force more vigorously during interactive joint tasks compared to friends.** Non-friends produced force with more vigour, as evident by higher peak RFD compared to friends in interactive dyadic and triadic trials. $^{*}p < 0.05$. P-values were derived using non-parametric permutation tests with FDR multiple test correction. RFD: rate of force production.

approximately 2s after trial onset in trials without continuous feedback, where participants made an initial prediction of the required force but in the absence of feedback did not need to adjust this prediction across the trial (Figure 5A). The sustained ERD may thus reflect ongoing attentional demands required to continuously monitor and adapt to visual feedback, consistent with previous findings reporting greater alpha ERD when dyads have visual contact and hence feedback of each other's movements (Tognoli et al., 2007; Zimmermann et al., 2022). The increased sustained ERD during continuous visual feedback trials was highly significant across the whole brain in solo, dyadic and triadic conditions compared with trials without continuous feedback (Supplementary Figure S9; $p \leq 0.001$), with clusters consistently spanning approximately 0.7s to 3s in theta, alpha and beta frequency ranges.

Finally, we examined whether ERDs differed between interactive and non-interactive conditions. Alpha and beta ERD were stronger during interactive trials compared to solo trials (Supplementary Figure S10; No Feedback Dyadic: $p = 0.016$, Triadic: $p = 0.51$; With Feedback Dyadic: $p = 0.002$, Triadic: $p = 0.017$), consistent with previous work reporting greater frontal and sensorimotor alpha suppression during social interaction (Tognoli et al., 2007; Perry et al., 2011; Naeem et al., 2012; Konvalinka et al., 2014; Zimmermann et al., 2022). One potential explanation is that interaction increases attentional demands by requiring participants to predict and monitor others' actions in addition to their own (Demos and Palmer, 2023). Taken together, these results indicate that non-friends allocate more attention to the task, particularly when continuous feedback requires ongoing monitoring and adaptation.

2.5 Non-friends exhibit increased neural inter-subject correlations

To further validate whether non-friends were more engaged during the task, we estimated inter-subject neural alignment using correlated components analysis (CorrCA, Parra et al. (2019)). CorrCA extracts neural components that are maximally similar across multiple individuals and enables com-

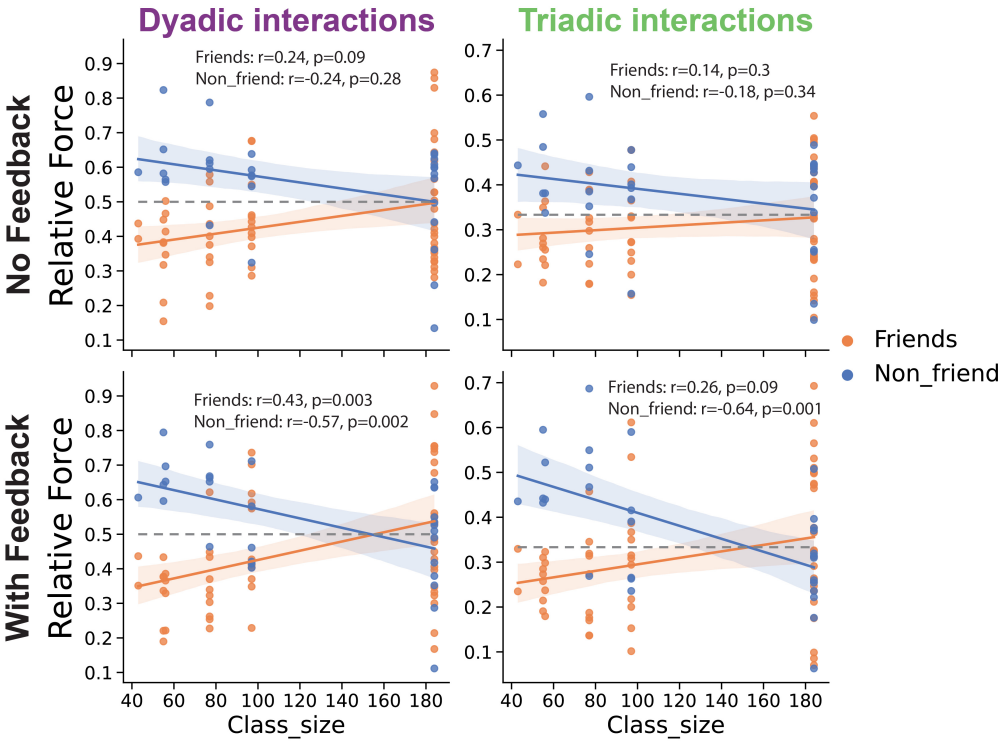

Fig. 4. **Greater force asymmetry was observed in smaller study line classes.** The effect of greater physical force produced by non-friends, and corresponding lower force by friends, was primarily observed for students recruited from smaller study line classes. The striped line corresponds to equal force contribution. Spearman correlation coefficients were computed and the p-values shown have been FDR multiple test corrected.

putation of inter-subject correlation (ISC) during stimulus-locked processing, which has been proposed as a marker of attentional engagement (Dmochowski et al., 2012, 2014; Poulsen et al., 2017).

Applying CorrCA to event-related alpha and beta power revealed three components with ISC values greater than chance level in both frequency bands (Figure 6A for alpha power and Supplementary Figure S11A for beta). For the leading correlated component, i.e. the component with the greatest ISC across participants, non-friends exhibited greater ISC compared to friends in trials with continuous feedback across both alpha (Figure 6B; FDR corrected p-values for Solo: $p = 0.014$, Dyadic: $p = 0.015$, Triadic: $p = 0.001$) and beta frequency bands (Supplementary Figure S11B; FDR corrected p-values for Solo: $p = 0.001$, Dyadic: $p = 0.001$, Triadic: $p = 0.002$). The associated topographic distribution for the leading components showed global activation across all channels, with slightly higher weights across lateral visual areas.

ISC was also higher for non-friends compared to friends in the second alpha correlated component in trials with continuous feedback (Supplementary Figure S12B; FDR corrected p-values for Solo: $p = 0.001$, Dyadic: $p = 0.003$, Triadic: $p = 0.001$). This component exhibited a topographic distribution over sensorimotor areas (C2 in Figure 6A)), indicating enhanced alignment of sensorimotor-related neural activity across non-friends.

To exclude the possibility that higher ISC in non-friends was trivially driven by larger ERD magnitudes, we repeated the CorrCA analysis on individual-level standardized event-related power. The friendship related ISC differences persisted under this normalization, primarily during trials with continuous visual feedback (Supplementary Figure S13), indicating that increased ISC reflects greater temporal alignment rather than differences in signal amplitude.

Finally, we assessed inter-subject neural alignment using a cluster phase-based inter-subject group synchrony metric (Richardson et al., 2012). This analysis revealed greater al-

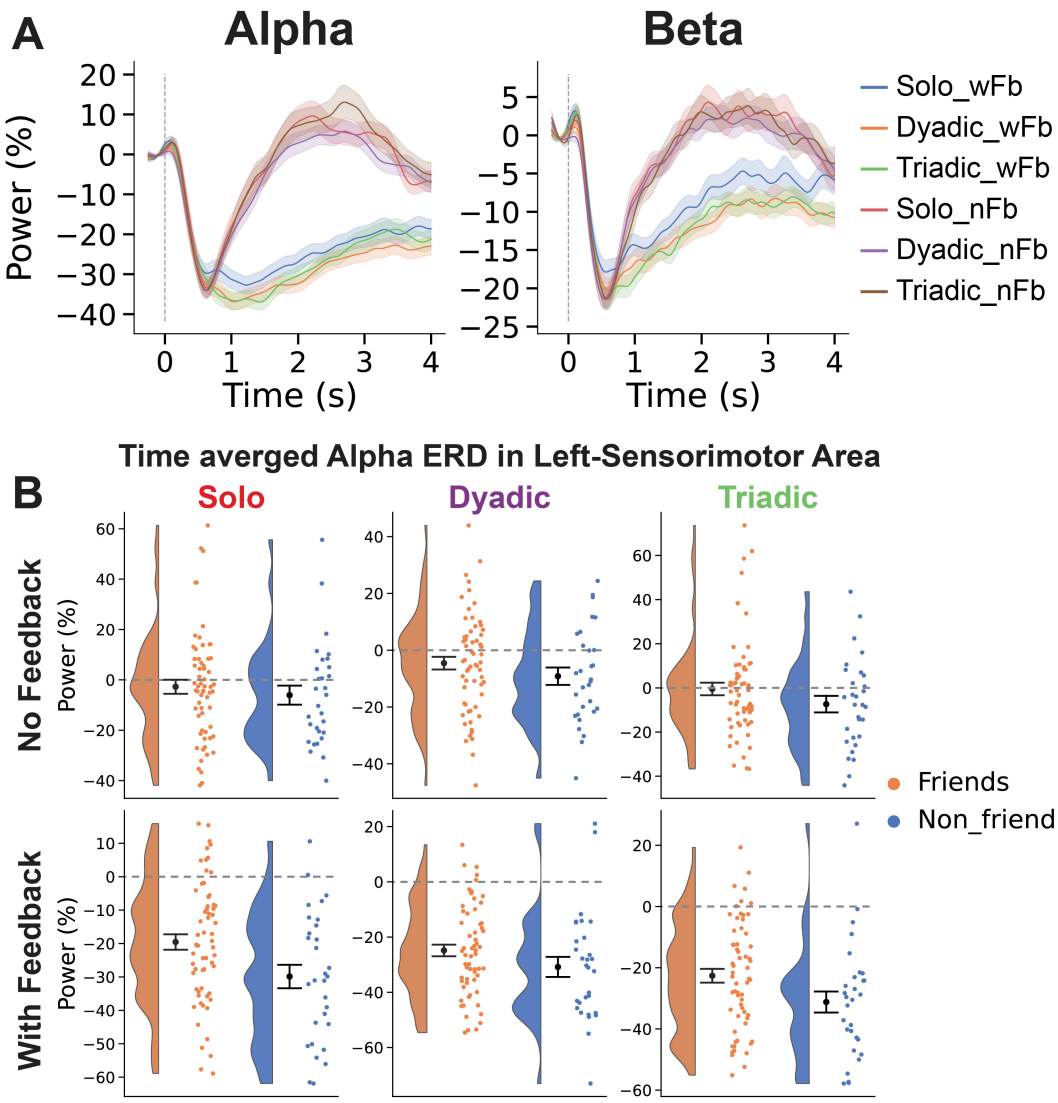

Fig. 5. **Non-friends exhibit increased alpha/beta event-related desynchronization.** A) Example plots of event-related power from electrodes above left sensorimotor area in alpha and beta frequency bands, color-coded based on the different interaction and feedback conditions. B) Time averaged event-related alpha power (0 to 4 seconds) from the left sensorimotor area, plotted separately for friends and non-friends. wFb: with feedback; nFb: no feedback, ERD: event-related desynchronization.

pha and beta group phase synchrony in non-friends compared to friends (Supplementary Figures S14 and S15), indicating that non-friends had greater phase-locked neural dynamics.

Taken together, these analyses show increased neural ISC and group phase-synchrony in non-friends compared to friends, indicating greater stimulus-locked neural responses. Based on previous experimental and theoretical research (Hasson et al., 2004; Dmochowski et al., 2012, 2014; Cohen et al., 2018; Rai et al., 2025), this suggests greater attentional engagement in non-friends during the Force Game.

3 Discussion

Human interaction depends on the ability to coordinate actions while simultaneously inferring others' behaviour, intentions, and levels of commitment (Sebanz et al., 2006; Michael et al., 2016; Vesper et al., 2017; Sebanz and Knoblich, 2021). In this study, we investigated how friendship versus non-friendship within real social networks modulate the behavioural and neural dynamics underlying group motor coordination. Across triads consisting of two close friends and

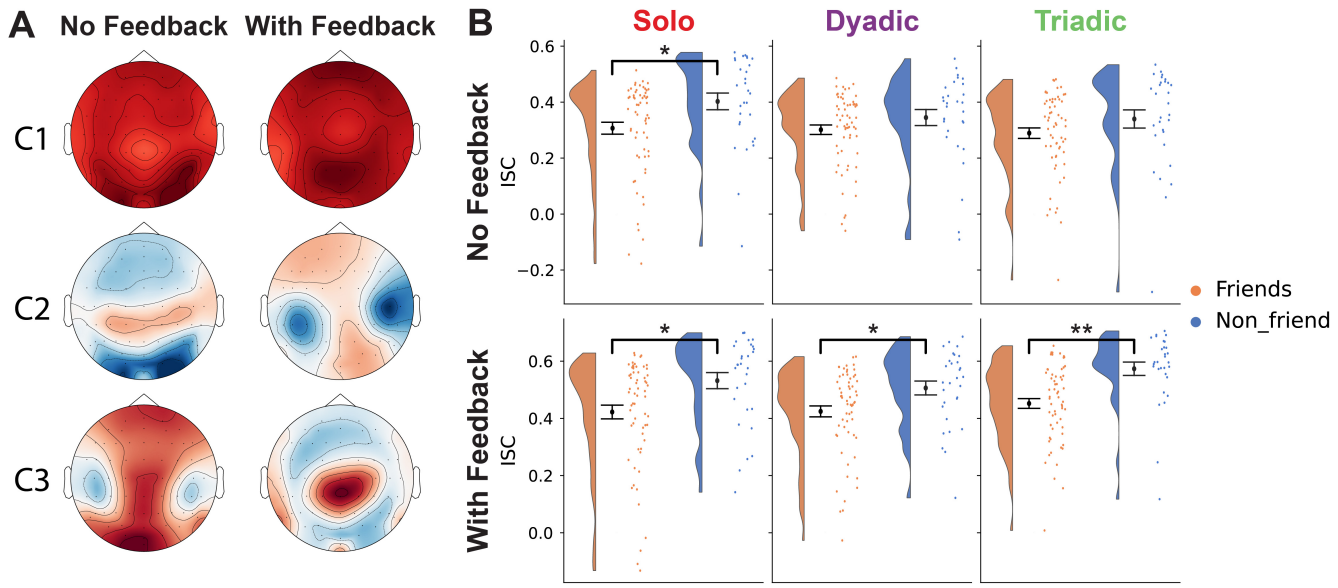

Fig. 6. **Non-friends exhibit increased inter-subject correlations.** A) Three correlated components fitted to alpha event-related power had ISCs above chance levels ($p < 0.05$ estimated with circular shifted surrogate data). B) For the leading component C1, which had the highest ISC, non-friends exhibited greater ISC compared to friends. The topographic maps correspond to projections of the forward model weights, where the polarity is normalized so the Cz electrode weight is positive. ISC: inter-subject correlation.

one non-friend, non-friends consistently produced greater and more vigorous physical forces than friends. In addition, non-friends exhibited greater alpha and beta ERD, higher neural ISC, and greater group phase synchrony than friends, neural markers associated with action-related and attentional processes. These effects were not explained by differences in maximal force capacity (Supplementary Figure S16) or baseline motor behaviour (i.e., RFD differences during solo conditions). Moreover, the greater alpha and beta ERD in non-friends could not be explained by the greater force produced, as ERD magnitude and amount of produced force were not correlated (Supplementary Figures S17 & S18). Together, these results indicate that the observed behavioural and neural differences between friends and non-friends reflect higher-level cognitive and motivational processes rather than basic motor or electrophysiological differences.

A central feature of the present design is relational asymmetry within each group, where two participants shared a close reciprocal friendship, whereas the third did not. One potential interpretation of the increased physical effort observed in non-friends is that they occupy a more uncertain social position within the group. Unlike the friends, whose mutual relationship affords predictability and social security, non-friends must infer both their functional role in the task and their relational standing relative to the others. In socially asymmetric group settings, this uncertainty may motivate individuals to invest more effort as a means of signalling commitment, competence, or value to the group (Leary and Kowalski, 1990; Williams and Karau, 1991; Pardede and Kovač, 2025). From this perspective, increased force production may serve as a compensatory strategy aimed at fostering affiliation or strengthening one's position within the interaction (Baumeister and Leary, 1995; Krishna and Götz, 2024).

Alternative but complementary mechanisms may also contribute to these effects. Friends may be more likely to distribute the work based on shared expectations and trust, potentially reducing individual contributions (Karau and Williams, 1993). By contrast, non-friends may experience greater uncertainty about the group dynamics, leading them to overcompensate (Williams and Karau, 1991). Moreover, interacting with familiar but non-friend partners may elicit heightened sensitivity to evaluation and feelings of exclusion (Baumeister and Leary, 1995; Holt-Lunstad et al., 2007; Maner et al., 2007), increasing arousal, attention, and engag-

ing mechanisms related to the need to belong (Baumeister and Leary, 1995; Williams et al., 2000; Pardede and Kovač, 2025). These mechanisms may have been further heightened by the fact that the non-friends in this study had fewer social relations in general relative to the friends (Supplementary Figure S1).

Consistent with this interpretation, force asymmetry was most pronounced among individuals drawn from smaller class networks, whereas no differences in force production were observed between friends and non-friends from larger classes. In smaller, more tightly knit social networks, individuals are more visible to one another and social interactions are embedded in denser relational structures, potentially amplifying sensitivity to evaluation and belonging (Zajonc, 1965; Tetlock and Manstead, 1985; Baumeister and Leary, 1995; Karau and Wilhau, 2020). In this context, increased force production may function as a behavioural signal of competence or willingness to affiliate. By contrast, in larger networks where interactions are more dispersed, reduced social exposure and weaker relational ties may attenuate these pressures, resulting in reduced behavioural asymmetry (Zajonc, 1965; Tetlock and Manstead, 1985; Karau and Williams, 1993; Baumeister and Leary, 1995; Karau and Wilhau, 2020). We additionally observed a trend indicating that non-friends with fewer close friends outside the class network tended to contribute greater relative force. Although this effect did not survive correction for multiple comparisons, it is consistent with the broader account that over-contribution among non-friends may be linked to increased motivation or arousal in social contexts where belonging is less secure (Zajonc, 1965; Tetlock and Manstead, 1985; Baumeister and Leary, 1995; Krishna and Götz, 2024).

The increased motor vigour observed in non-friends further supports this interpretation. Movement vigour has previously been linked to reward, motivational states, and commitment (Desmurget and Turner, 2010; Thura and Cisek, 2017; Marinovic et al., 2017; Shadmehr et al., 2019; Marbaker et al., 2025). Increased vigour in the absence of external incentives therefore indicates a stronger internal motivation to succeed in the joint task. In the present social context, the increased physical effort and vigour may reflect a heightened motivation to signal commitment and competence to familiar but non-friend partners, potentially as a means of reinforcing social inclusion (Leary and Kowalski, 1990; Williams and Karau, 1991; Baumeister and Leary, 1995; Shadmehr et al., 2019; Krishna and Götz, 2024; Marbaker et al., 2025; Pardede and Kovač, 2025). At the same time, the asymmetric social group configuration may differentially modulate arousal, with friends being more relaxed and non-friends experiencing elevated arousal due to social uncertainty. As arousal-related neuromodulatory systems can modulate force output independently of motivational processes (Jahn et al., 2018), both heightened motivation and increased arousal may have contributed to the greater physical force and vigour observed in non-friends (Zajonc, 1965; Karau and Williams, 1993; Jahn et al., 2018; Marbaker et al., 2025).

The neural results further indicate that non-friends were more engaged during the task. Non-friends showed stronger alpha and beta event-related desynchronization - proposed neural markers of attention, motor preparation, execution, and prediction (Klimesch, 1999; Pfurtscheller and Lopes da Silva, 1999; Buschman and Miller, 2007; Klimesch et al., 2007; Klimesch, 2012; Kilavik et al., 2013; Stecher et al., 2025) - particularly during conditions requiring continuous monitoring and adaptation to visual feedback of the group force. The alpha and beta ERD was also greater during interactive conditions compared to solo conditions, consistent with previous findings showing that social interaction recruits more motor and attentional resources (Perry et al., 2011; Konvalinka et al., 2014; Zimmermann et al., 2022). These effects were accompanied by higher stimulus-locked inter-subject correlation and greater group cluster phase synchrony (Richardson et al., 2012), suggesting more aligned neural processing across non-friends (Dmochowski et al., 2012, 2014; Cohen and Parra, 2016; Parra et al., 2019; Lambrechts et al., 2025). Together, these neural signatures indicate heightened attentional engagement with the task and feedback signal among non-friends relative to friends.

While the behavioural effects of friendship were observed for both feedback conditions, neural differences notably emerged exclusively with continuous visual feedback. This suggests that relational context primarily modulates neural processing during phases of interaction that require fine-grained, ongoing sensorimotor adaptation. The temporal profile of the ERD clusters, spanning the period following the initial force ramp-up, corresponds to a phase during which participants actively fine-tuned their force contribu-

tions around the target. In contrast, this adaptive phase was absent in trials without continuous visual feedback, where participants had to rely on internal predictive models rather than ongoing correction in response to sensory feedback, indicating that the task demand differences may mask the relational effects at the neural level.

At first glance, our findings of greater neural similarity among non-friends may appear inconsistent with prior social network neuroscience findings showing that friends tend to exhibit more similar neuroanatomical features (D'Onofrio et al., 2022), intrinsic resting-state neural activity (Hyon et al., 2020b), and stimulus-evoked neural responses during passive video watching (Parkinson et al., 2018; Hyon et al., 2020a; Shen et al., 2025). Similarly, a prior study of real world social networks has shown that highly-central individuals are more sensitive to social exclusion by strangers, contrasting with our findings (Baek et al., 2025). However, the interactive nature of the current task differentiates it sharply from prior paradigms. Here, neural similarity is driven by active task-evoked, stimulus-locked processing rather than intrinsic similarity in resting-state activity or perception during passive viewing. In this setting, stronger ISC in non-friends reflects greater alignment to the active task itself, rather than stable similarity in neural representations. Similarly, the behavioural asymmetry emerges during active interaction, and in a group social context where the more central individuals interact in the presence of their close friend.

Despite the interactive nature of our task, several limitations should be considered. Although our paradigm offers a controlled means of quantifying joint motor coordination, it captures only one facet of social group behaviour, and the effects and dynamics of friendship may differ in tasks involving other social, cognitive, or motivational demands (Zajonc, 1965; Karau and Williams, 1993), e.g., face-to-face verbal interactions (Sievers et al., 2024). In addition, social network analyses were constrained by incomplete network coverage, limiting estimation of higher-order network metrics to self-reported outdegree and class network sizes. On average 66.4% of the students across all seven study lines reported their connections, hence reliable estimation of network parameters such as eigenvector centrality, density, clustering, and assortativity was precluded (Kossinets, 2006; Smith and Moody, 2013; Marks et al., 2013). The unique triad composition of two close friends and one non-friend from a shared class social network also posed recruitment challenges which limited our sample size. Finally, given that there were also differences in outdegree centrality among friends and non-friends, future work should disentangle effects related to the relational asymmetry in the group composition and the overall standing in one's class networks, as captured by centrality measures. Nonetheless, by combining network structure, real-world relational context, real-time behavioural coordination, and multi-brain EEG, this study provides a novel approach to understanding how social relationships are embodied during interaction.

In summary, our findings demonstrate that differences in social relationship - friend versus non-friend - can systematically bias how individuals allocate physical effort, attentional resources, and neural engagement during group coordination. Non-friends appear to over-contribute, both behaviourally and neurally, potentially reflecting increased evaluative concern, uncertainty, or motivation to belong in socially asymmetric groups. Friends, by contrast, show behavioural mechanisms consistent with reduced vigilance in relation to non-friends, and potentially, social loafing. These results underscore the importance of incorporating relational context into joint action studies, and provide a neurobehavioural framework for understanding how social structure influences collective action.

4 Methods

4.1 Social network mapping

378 students, across seven bachelor program study lines (with sizes ranging from 43 to 184 students, $M = 83.14; SD = 44.26$) at the Technical University of Denmark (DTU), gave informed consent to have their social networks in their study line programs mapped. Specifically, 28 to 113 ($M = 54.0; SD = 27.09$) students per study line filled our questionnaire, corresponding to a response rate ranging from 50.6% to 95.7% ($M = 66.4\%; SD = 13.05\%$) of the size of the study line classes.

In practice, we entered the classrooms, gave a brief 5 min presentation about the project and experiments, and asked students to fill out questionnaires in which they checked off the fellow students they considered a friend (defined as *a person whom you like to spend your free time, enjoy informal so-*

cial activities, such as going for lunch, dinner, drinks, films, etc., and help each other out in a practical way) (Burt, 1995; Spencer and Pahl, 2006; Parkinson et al., 2018; Sievers et al., 2024), or close friend (defined as *a person whom you not only help each other and enjoy each other's company but also share personal information and provide emotional support*) (Spencer and Pahl, 2006), or leave it blank to indicate the fellow student was not a friend (Figure 1A). The social network surveys were administered during the students' first (2nd semester) or second (3rd or 4th semester) academic year in their bachelor program, as the courses taken by the students' in the early semesters of their bachelor programs are primarily mandatory courses, hence the students have a high overlap of common courses within each study program.

Participants recruited for the experiment were also asked to fill an additional questionnaire about their friends and close friends outside their study programs, divided into workplace, hobby-related, social media, studies and "other" categories to promote recall, upon arriving in the lab.

4.2 Experimental participants

From the social networks, 93 healthy right-handed participants (35 females) between the ages of 18 to 35 years (mean = 21.4, SD = 2.29) were recruited and gave informed consent to participate in the experimental task. Triads consisted of two reciprocal close friends and one non-friend from the same study program. The study was conducted according to the Declaration of Helsinki and was approved by the Scientific Ethics Committee for the Capital Region of Denmark (H-23013244). Participants in the experimental task were financially compensated for their participation.

4.3 The Force Game paradigm

The three participants sat facing away from each other, inside an electrically shielded room, in a triangular formation with 50 cm between each pair of chairs (Figure 1B). Each participant had a screen, placed 60 cm in front of the center of each chair, that displayed the experiment (Figure 1C). Each participant was equipped with a custom-made 3D printed pressure measuring (force) device, which we calibrated using a set of weights (295g, 500g, 1000g, 2000g and 5000g) to estimate the forces in Newtons (Supplementary Figure S19). The participants were instructed to hold the force devices with their right hand and press with their right thumbs to reach a target force, either individually or jointly. The screens would display the force (either solo or joint) as an expanding white circle (the bigger the force, the larger the circle) and the target force as a hollow blue circle. When the produced force was within $\pm$ 2N of the target force, the whole circle would turn blue indicating the participants successfully arrived at the target. The participants were explicitly instructed to keep the force at the target for the whole duration of the 4 second trial, upon reaching the target. The radius of the displayed force and target force was based on the log-transformed forces in Newtons, to be visually sensitive to smaller forces. Practice trials were also performed prior to the experiment, to familiarize the participants with the devices, where the participants were instructed to freely press, press as hard as they could and reaching the target force individually or jointly with and without continuous visual feedback. Preliminary pilot runs estimated 50N as a reasonable max force and in order to enable all participants to be able to reach the target and taking fatigue into account, we set the target forces to vary as 8N, 10N, 12N, 14N or 16N (corresponding to around 15 to 30% of max force production). The averaged max force during the practice trials from all 93 participants was 49.59N, confirming our pilot results.

The experiment consisted of 300 trials, across 10 conditions with varying group sizes (solo, duo and trio) with and without continuous visual feedback. There were three duo tasks, i.e. P1 and P2, P1 and P3 or P2 and P3 interacting while the last participant's force contribution was excluded from the joint force, a manipulation they were not aware of. In group trials, only the averaged collective joint force was shown, and the contribution from each participant was $1/2$ or $1/3$ the actual individually measured force in the duo and trio trials respectively, to take into account the increase in group size. Additionally, we manipulated whether the interaction recruited adaptive or predictive mechanisms, by either giving them continuous visual feedback, or no feedback across the 4-second trial, followed by discrete feedback of the reached force at the end of the trial. During the experiment, each condition was performed in blocks of five trials, corresponding to the five target forces (in randomized order), followed by a self-paced break. Prior to each 4 second trial, a fixation cross was presented on the screen (jittered 1 to 2 seconds duration, randomized for each trial to prevent EEG synchronization due

to the predictability of stimulus onset timing). Prior to each block, a condition cue was presented with the text *Individual Task* or *Group Task* followed by a green emoji with a single person or an orange emoji with three people, and the text *Continuous Feedback* or *No Continuous Feedback*. No distinction in condition cue were given for duo or trio trials, and no explicit information about who was excluded in duo trials was provided. For trials with no continuous feedback, only the hollow blue circle corresponding to the target force was shown during the 4 second trial, followed by a static image of the joint force at the end of the trial, shown for 1 second. All 10 conditions were also administered in blocks (in randomized order), repeated six times (Figure 1C), to avoid the same conditions being consecutively performed (on top of the 5 repeated trials). Longer forced breaks of 1 min were also given once 100 or 200 trials had been completed to ensure the participants relaxed their thumbs. While performing the Force Game, simultaneous EEG was recorded. The experiment was designed using Psychopy (Peirce et al., 2019) and took around 45 min, and the whole procedure including EEG setup and questionnaires took around 1 hour and 30 min.

4.4 Data acquisition

The custom-made force devices send a constant voltage to the Arduino, which converts the analogue voltage signal to a digital 8 bits signal and transfers it to the stimuli PC. The force devices have a pressure-sensitive button, which changes the resistance when pressed and thus the voltage will change accordingly. Based on the calibrations with constant weights, we observed measurement errors in the range of 0.1N. Each force device sends a continuous stream of numbers (more than 1000/sec), and to synchronize the measurements we stored the force measurements corresponding to when the screens updated the visual display. This resulted in the behavioural force data being acquired at 25 Hz. Despite having 60 Hz monitors, it took computational time to visually create the elements and display on the three screens simultaneously from one PC, hence the update frame rate and sampling rate was lower than 60 Hz. Nonetheless, visual inspection of the stimuli confirmed that 25 Hz was enough for the trials to visually seem continuous, and 25 Hz was enough to capture smooth force trajectories.

EEG was recorded using three synchronized, daisy-chained 64-channel Biosemi (Amsterdam, The Netherlands) ActiveTwo EEG set-ups in a 10–20 system, at a sampling frequency of 2048 Hz. EEG caps with 64 channels were positioned such that Cz was centered on the head, at the midpoint between the nasion and inion, and the left and right ear. Conductive gel (SignaGel Electrode Gel, Parker Laboritories, Farfield, NJ) was used to improve signal reception, and electrodes with offsets above $\pm$ 20 mV was adjusted in order to keep them as close to 0 as possible. Any visually bad electrodes at recording was noted down for exclusion during preprocessing.

The data from one participant was excluded from analysis, as it was clear from the behavioural force trajectories that the instructions were not followed (not pressing at all in many trials, resulting in failing to reach the target force in half of solo conditions with feedback, where the average for participants is 98.9%). This means the solo, duo and trio conditions involving the non-compliant participant was discarded, but the solo and duo conditions with the remaining two participants in the triad was kept.

4.5 Behavioural analysis

The behavioural force measurements were linearly interpolated to common timepoints, in fixed 40 ms intervals (25 Hz) starting from trial onset to end of trial at 4 seconds, in order to analyze across trials. A successful trial was defined as a trial where the force trajectory (solo or group) reached within $\pm 2N$ of the target force, and stayed at the target for 200 ms. The accuracy (success rate), latency to success and stability (duration the force stayed around the target) was computed. Relative force was computed as the relative force contribution in group tasks at time of success. The instantaneous rate of force development (RFD), defined as the first derivative of the force time series, was approximated by taking the difference in force between each sample, divided by the time difference: $RFD = \Delta F / \Delta t$. Coefficient of variability was computed 2 s after trial onset, to avoid the build-up of force when approaching the target, while focusing on the part where participants had to stay around the target. The 10 experimental conditions were collapsed into 6 conditions (3 x 2, corresponding to group size x visual feedback), by combining the two duo conditions where each participant were actively contributing to the joint force, and removing the duo condition that each participant was excluded from. The same 6 collapsed conditions were applied for EEG analysis.

4.6 EEG preprocessing

The EEG data were processed using MNE-Python 1.6.1 (Gramfort et al., 2013). First, the data were bandpass filtered at 1–40 Hz (Hamming), downsampled to 500 Hz, and segmented into epochs (-0.5 to 5.5 seconds relative to trial onset). Bad epochs and channels with gross artefacts were rejected by visual inspection. The bad channels were interpolated from adjacent channels using spherical spline interpolation (Perrin et al., 1989) followed by re-referencing to the common average. Ocular, heart and muscle related artefacts were removed using independent component analysis with the number of components set to 32. The automatic detection of muscle-related components in MNE-python were employed to guide the manual determination of muscle artefacts. Autoreject 0.4.3 (Jas et al., 2017) was employed to catch any remaining artefacts by interpolating specific bad channels within each epoch, followed by a guided final manual visual inspection with highlighted bad epochs determined by the algorithm. Using Autoreject this late in the preprocessing pipeline made it prone to false-positives if the signal was already clean, hence a manual check was performed and no epochs were dropped automatically. On average 3.45 (SD = 5.12) number of epochs were dropped, 1.1 (SD = 2.4) number of channels were interpolated and 15.66 (SD = 4.27) independent components were corrected. The EEG features were estimated in the five canonical frequency bands: delta (1–4 Hz), theta (4–8 Hz), alpha (8–13 Hz), and beta (13–30 Hz).

4.7 Event-related power

The time-frequency representation (TFR) of the epoched EEG data was computed using Morlet wavelets. We used a variable temporal window length (decreased temporal window with increased frequency), to obtain greater temporal resolution at higher frequencies. The power was computed for each frequency band and averaged across epochs for each of the 6 collapsed conditions. Percentage based baseline correction was applied on the averaged time-frequency representation using the pre-stimulus interval (-250 – 0 ms), i.e. on a single-subject level for each condition to avoid positive bias from performing percentage based baseline correction on a single-trial level (Hu et al., 2014).

4.8 Inter-subject correlation

ISC was estimated using correlated component analysis (Parra et al., 2019). Specifically, for each frequency and condition, we applied correlated component analysis on the TFRs, with participants on the first axis to compute stimulus-related power components that maximally correlates between subjects. To determine similar components across group size conditions (but separately for visual feedback), we concatenated the different group conditions along the first axis, in order to make ISC values comparable across group sizes. Importantly, to account for the positive bias induced by higher SNR in the TFRs from the collapsed duo condition (60 trials as opposed to the 30 trials), we performed CorrCA and calculated ISC separately for TFRs computed from each of the two uncollapsed included duo conditions for each participant, followed by averaging after ISC was computed, as a higher SNR condition can arbitrarily increase inter-brain synchrony estimates (Zimmermann et al., 2024). To determine an effect of friendship, ISC was separately computed among friends and among non-friends, using all-to-all pairwise Pearson's correlations of the extracted components. To ensure the observed difference in ISC was not confounded by a difference in number of subjects for each group (2 friends for each non-friend), we performed 1000 permutations where we performed the ISC estimation on 30 randomly sampled friends (without replacement) to create a null distribution and no difference was seen compared to the mean ISC for the original full sample of friends (lowest $p = 0.951$ across alpha/beta ISCs across all conditions). To rule out the increased ISC in non-friends were driven by increased ERD in non-friends, we also repeated correlated component analysis on subject-level standardized TFRs and observed the same results.

4.9 Group cluster phase synchrony

Group cluster phase synchrony was estimated following Richardson et al. (2012). Briefly, event-related potentials were computed by averaging across epochs for each condition, followed by filtering for each canonical frequency band. Hilbert transform was applied to estimate the analytic signal, and the phase was extracted. The group cluster-phase time series was estimated as the averaged phase time series across individuals, from which relative phase time series for each individual could be computed, followed by estimation

of the degree of synchrony for each individual with respect to the group. Conceptually, the method is similar to the classical connectivity metric phase-locking value (Lachaux et al., 1999), except relative phase is not computed between individual electrodes or subjects, but between each individual to the group, for each electrode. Similar to ISC, we accounted for potential positive bias induced by higher SNR from collapsed duo conditions by performing the inter-subject analysis separately for each uncollapsed condition, before averaging the duo conditions after group synchrony was computed. To determine an effect of friendship, group cluster phase synchrony was separately computed among friends and among non-friends.

4.10 Statistical analysis

Results are shown as mean with standard error bars. Non-parametric permutation tests (10000 permutations) with FDR correction was used to test for group mean differences. The FDR correction was applied to each metric separately, but across conditions. QQ-plots were assessed to evaluate for normality, and Spearman's correlation was used to test for significant correlations. The number of asterisks corresponded to each of the following significance levels: $^{*}p < 0.05$, $^{**}p < 0.01$ and $^{***}p < 0.001$.

Non-parametric cluster-based permutation tests (Maris and Oostenveld, 2007; Sassenhagen and Draschkow, 2019) were applied to handle the multiple comparison problems when taking time, space (electrodes) and frequency into account for estimating group differences in ERDs and group cluster phase synchrony. 1000 permutations were used for ERDs, due to high computational demand with the high dimensionality over time, space and frequency, while 10000 permutations were used for group cluster phase synchrony that only had space and frequency. A T-statistic with cluster forming threshold of 2 was employed. For all statistical tests, a p-value < 0.05 was considered significant for rejection of the null hypothesis.

Data and code availability

The EEG data and code that support the findings of this study are openly available on https://lab.compute.dtu.dk/glia/force-game-eeg-analysis.

Author contributions statement

Q.L. and I.K, conceived and designed the study and experiments. Q.L., A.D., K.K., and I.K. conducted the experiment and collected the data. Q.L. implemented the code. Q.L. and I.K. designed the analysis and generated the first draft of the manuscript. Q.L., A.D., K.K., and I.K. contributed to interpretation of the results and reviewed the manuscript.

Declaration of Competing Interests

The authors take full responsibility for the content of the publication. We declare we have no competing interests.

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