

# EEG correlates of haptic interaction with human and robotic partner

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**Abstract**—To move a table or dance together, people do not rely heavily on verbal communication; instead, they coordinate their actions through the exchange of force and touch information. While this *haptic communication* is well understood at the behavioural level, its underlying neural processes remain poorly characterized. This study investigates the cortical mechanisms driving haptic communication during a tracking task performed by solo individuals, human dyads, or between a human and a robot partner. A dedicated dual wrist robotic interface enabled us to systematically analyse the effect of specific sensory feedback modalities while recording cortical activity via electroencephalogram (EEG) hyperscanning. Consistent with previous findings, the results showed that the brain regions associated with haptic communication are in the frontal and the occipito-parietal areas. In these areas, synchronisation between the cortical signals of the two partners in a dyad increased when they were connected, or when they simultaneously received similar haptic feedback. The analysis of the complexity of the cortical signals via fuzzy entropy, indicated that stronger force feedback is associated with higher entropy in the areas involved in motor planning and multisensory integration. Most metrics did not reveal a difference between the human-human interaction and the human-robot interaction, except for a stronger inter-brain synchrony (IBS) around the right temporo-parietal junction (rTPJ) during human-human interaction. Using well-controlled conditions with a dedicated robotic interface and hyperscanning EEG recording, we could distinguish the dyadic conditions from the Solo condition with the brain synchronisation, Power Spectral Density and fuzzy entropy metrics, and observed a stronger IBS around the rTPJ in human dyads compared to human-robot dyads.

**Index Terms**—Haptic communication; EEG hyperscanning; Entropy; Inter-brain synchrony; Human-robot interaction; Human-human interaction

## I. INTRODUCTION

When ice skating for the first time, holding the hand of an experienced skater may instil confidence and enhance performance. What are the underlying factors of this improvement?

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Does it stem from the social aspect of touch, the interaction forces, the vision of the partner's movements, or a combination of these elements? To understand the sensorimotor exchange during collaborative activities, we have developed a tracking task paradigm, in which dyads of participants are connected by a virtual elastic band [1]. This connection facilitates tracking and learning in both partners [2], such that even the more skilled partner benefits from interacting with a less skilled one. This phenomenon has been confirmed in experiments of our and other groups using tasks with one, two, and three degrees-of-freedom [3]–[5].

What drives the performance enhancement during sensorimotor interaction? While partners typically perceive the interaction force as a disturbance and are not aware of its supportive role [1], their brain recognizes that the forces they feel are related to their visual task, and integrates the partner's movement to optimize performance [3]. More specifically, this *haptic communication* (HC) arises as the partners exchange their motion plan. Interestingly, when the computational mechanism of HC is implemented on a robotic interface, the interaction with this *robot partner* yields similar performance and learning benefits as with a human partner [2], [3] and is perceived similarly [6].

Although HC has been well-characterized at the behavioural level, its underlying neural mechanisms remain unclear. Beyond activation in motor and sensory areas involved in movement and visuo-haptic processing, HC may also engage multisensory integration and social brain regions. However, research on the neural dynamics of human haptic interactions is limited, with most studies on brain activity during joint actions focusing on social activities that do not involve the exchange of haptic information.

In this regard, research on interpersonal coordination has shown that people align attention, emotions, actions, and thoughts to engage socially [8]. Studies have also demonstrated increased activation in specific sites of the human mirror system during joint actions [9]. Furthermore, when people work together in social tasks, neural synchrony, between them is often higher than during solo performance. This has been observed in tasks like rhythmic limb coordination [10], spontaneous mirroring of hand movements [11], mutual gaze tasks involving finger pointing [12], and collaborative motor activities [13]. When cooperating in cognitive tasks, inter-brain synchrony (IBS) in the alpha and beta bands is significantly higher than in competitive scenarios [14]. Additionally, alpha suppression is more pronounced in centro-parietal areas during

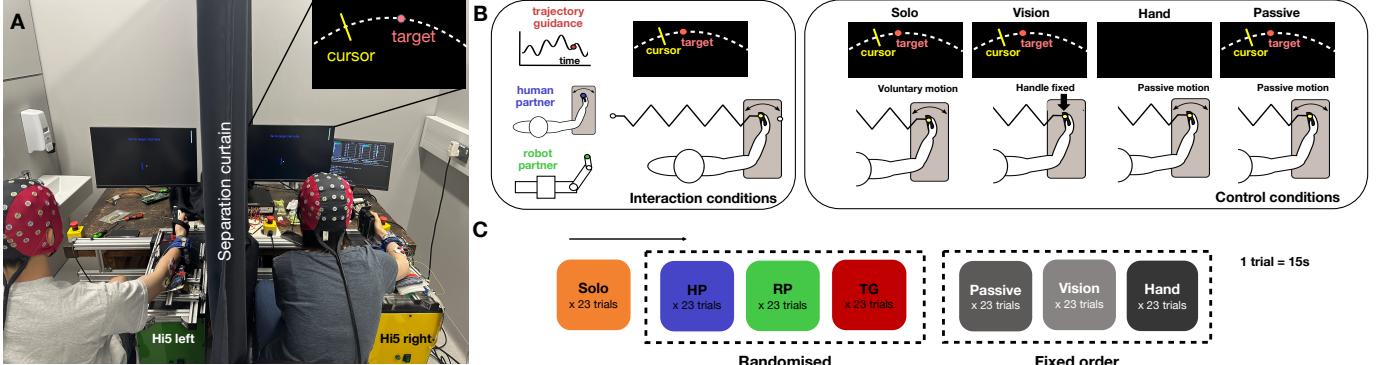


Fig. 1: Systematic investigation of neural correlates of haptic communication. A. Experimental setup to study brain activity during human-robot and human-human interaction. Computer-controlled haptic feedback is provided through the Hi5 dual robotic interface [7]. Participants interacted during wrist flexion/extension movements. The cortical activity is recorded using an EEG hyperscanning system. B. Three interaction conditions (i.e., with a partner) and four control conditions are tested, where the different sensory modalities involved in each condition are presented in Table I. C. Experimental protocol.

body coordination compared to non-interactive tasks [15], and there is an increase in beta and gamma synchrony between specific brain regions of the “model” and “imitator” during coordinated hand movements [11].

The tasks used in the aforementioned studies did not involve a haptic connection between participants. A pioneering fMRI study analysed the neural correlates of haptic interaction in professional dance partners holding hands, while they were asked to imagine dancing and assume leader/follower roles [16]. Increased activity was observed in frontal and temporo-parietal areas associated with the understanding of others’ mental states and the prediction of their intention. However, while this study involved direct physical contact, it only recorded the cortical activity of one partner, relied on task imagery rather than actual performance, and did not capture additional physiological data.

In this context, we decided to systematically investigate the cortical correlates of HC in dyads carrying out a tracking task while connected by a virtual elastic band. Each partner controlled a cursor on an individual monitor using their right wrist flexion/extension movement through a dedicated dual robotic interface (Fig. 1 A). We compared the interaction with a human partner, a robotic partner and the robotic guidance typically used in training robots (Fig. 1 B). Additionally, we used different control conditions to identify the role of different sensory modalities involved in this visuo-motor task: vision, proprioception, haptic feedback and volition, as described in Table I. This enabled us to systematically test and understand the impact of these sensory modalities on the neural mechanisms of HC.

To analyse the brain mechanisms driving HC, we first explored the *power spectral density* (PSD) of the cortical signals, where the PSD during the task would indicate relevant brain areas and frequency bands. The EEG hyperscanning setup allowed to compute *inter-brain synchrony* (IBS) of the participants in the dyads, as it can be associated with shared attention and information exchange during social or

collaborative tasks [13], [14], [17]. *Fuzzy entropy* was also used to estimate the complexity of the EEG signals and capture the dynamics of brain activity [18]–[20].

Given the social nature of HC, our first hypothesis (H1) posits that the brain regions and frequency bands engaged in HC will correspond to those typically activated during social interactions. Our second hypothesis (H2) predicts that specialized brain regions will respond differently depending on the experimental interaction conditions. Specifically, we expect that brain areas associated with social cognition will distinguish between human and robotic partners (H2.1), while regions involved in motor planning and execution will differentiate solo trials (i.e., no mechanical connection) from interactive trials (H2.2). Furthermore, we hypothesize that regions associated with tactile feedback processing will be modulated by the strength of the haptic connection (H2.3). Finally, we anticipate that IBS will be lowest during solo trials and highest when participants work with a human partner, indicating stronger collaboration (H3).

## II. RESULTS

Using the Hi5 dual robotic interface (Fig. 1 A) [21], 24 participants (in 12 dyads) carried out our experiment. The two participants of a dyad were separated by a curtain preventing visual communication, and controlled a cursor displayed on an individual monitor using wrist flexion/extension of their right hand to track a target moving along a multi-sine function. Each participant was asked to track the target “as accurately as possible”, or to stay relaxed (see Methods). This setup enabled us to implement various experimental conditions and systematically study the role of specific sensory feedback conditions (Table I). In some conditions, the two partners were connected to each other or to a robot by a virtual elastic spring (Fig. 1 B).

To contextualize the results within the findings of our previous study investigating the behavioural mechanisms of HC [6], we used the same three interaction conditions: *human partner*

(HP), *robot partner* (RP), i.e. a human-like tracking and interaction algorithm [3], and *trajectory guidance* (TG) where a spring-like force is connected to the target, as is traditionally used in robot-assisted applications. Four control conditions, each corresponding to one sensory modality involved in the task execution, were designed to identify cortical activity associated with non-partner related feedback (see Table I). These involve: (i) task execution *without a connection with a partner* (Solo), (ii) *visualisation of cursor movement* without wrist motion (Vision), (iii) relaxed wrist while being *passively moved by the robot* without visual feedback of the cursor (Haptic), (iv) relaxed *passive motion with TG* (Passive).

We explored the brain mechanisms underlying HC using scalp plots and PSD analysis, fuzzy entropy, and IBS analyses. Scalp maps were used to examine changes in the activity of the different brain regions and frequency bands across conditions. Fuzzy entropy was calculated to explore the complexity of cortical signals across the brain areas of interest, where higher fuzzy entropy values suggest more complex, less predictable brain patterns, often reflecting increased cognitive engagement. IBS was used to quantify the physiological synchronisation of neural activities within the twelve dyads during the joint target-tracking task, and to compare it across experimental conditions. Stronger cortical synchronisation between partners is commonly associated with social connection, coordination and cooperation, and hence may reflect ongoing exchange of haptic information between partners.

#### A. Neural Dynamics of Social Haptic Interaction

Fig. 2 A illustrates the power distribution of various frequency bands (in each row) under each interaction type (in each column). When an individual performs the task on their own (Solo), the cortical patterns seem to differ greatly from those of all other conditions. Activity within the three interaction conditions RP, HP, TG, as well as within the three relaxed control conditions Vision, Haptic, Passive, looks similar. Slight differences can be observed between the interaction and the relaxed conditions, such as stronger frontal activation in the interaction conditions. Differences can also be observed across all frequency bands, which was expected, since each frequency band is related to different aspects of behaviour.

Fig. 2 B, C shows statistical differences (at  $p < 0.05$ ) in PSD between the interaction conditions and the control conditions, in the three frequency bands of interest. Fig. 2 B (first row) shows that, compared to Solo, the interaction conditions exhibit differences in activation (black dots) in

TABLE I: Sensory feedback modalities involved in each partner and control condition.

Condition	Vision	Haptic interaction	Proprioception	Volition
Solo	✓		✓	✓
Vision	✓			
Haptic		✓	✓	
Passive	✓	✓	✓	
RP, HP, TG	✓	✓	✓	✓

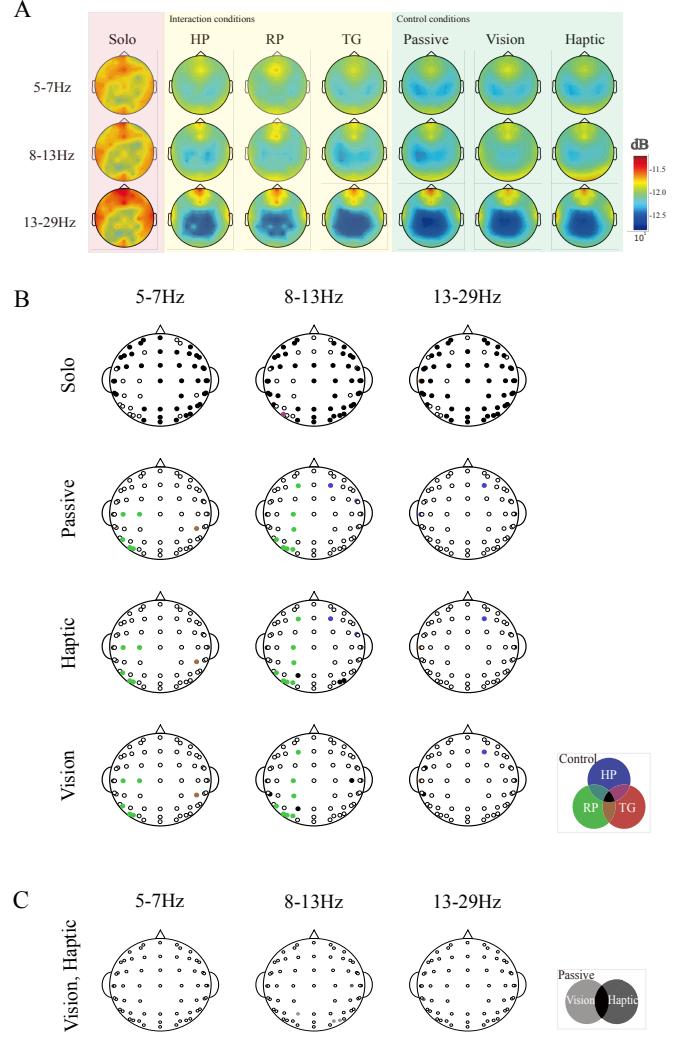


Fig. 2: Cortical activity maps. (A) The scalp plot for seven experimental conditions. Rows correspond to the frequency power distribution at theta (5-7 Hz), alpha (8-13 Hz), and beta (13-29 Hz) bands. (B-C) Differences in EEG activity across experimental conditions using PSD in the theta (5-7 Hz), alpha (8-13 Hz), and beta (13-29 Hz) bands and Wilcoxon signed-rank tests with Benjamini-Hochberg correction. Channels that are significantly different ( $p < 0.05$ ) among conditions are coloured according to the legend. Detailed explanations for the legend can be seen in the Appendix, Fig. 5. (B) show the differences between the three interaction conditions and the four control conditions (Solo, Passive, Vision, and Haptic); (C) compares Passive to the two perceptual conditions (Vision, Haptic).

all three frequency bands and across a wide area. This area includes the frontal cortex, sensorimotor cortex and occipito-parietal region, which are known to be involved in motor planning and integration of multi-sensory feedback. Although all interaction conditions are different from Solo in these areas, no statistical differences are observed between them.

We also compared the relaxed control conditions, i.e. Passive, Haptic and Vision to the three interaction conditions (Fig. 2 B, second to fourth rows). Here, we observe differences in PSD in the sensorimotor cortex and occipito-parietal areas

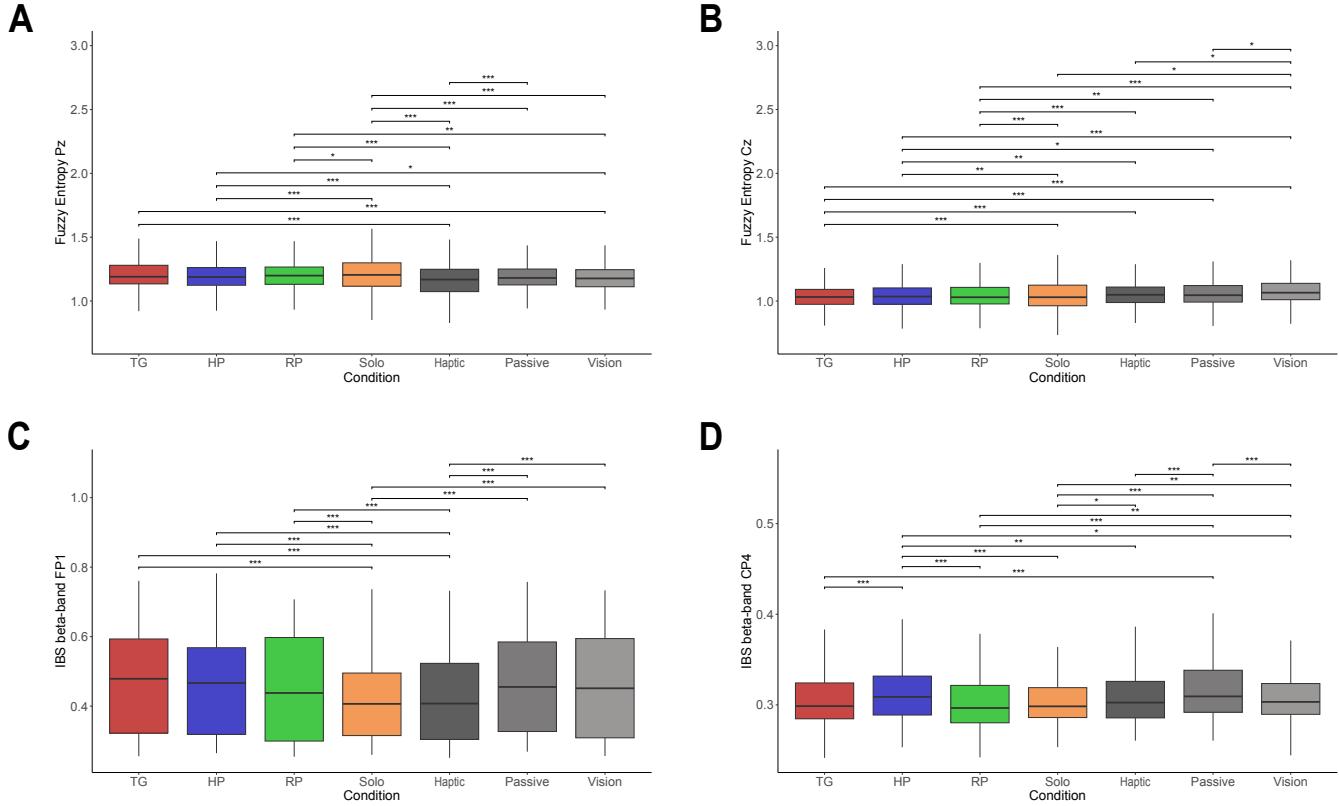


Fig. 3: Fuzzy entropy and IBS results. (A) Fuzzy entropy of the Pz channel at haptic feedback area for each condition. (B) Fuzzy entropy of the Cz channel at motor planning area for each condition. (C) Beta band IBS of the FP1 channel at social interaction area. (D) Beta band IBS of the CP4 channel at social interaction area.

for the theta and alpha bands, between RP and Passive, Haptic, and Vision (green dots). In specific channels in this area, HP and TG are also different from Haptic and Vision for the alpha band (black and brown dots). This may be due to the individual's movements in the interaction conditions and the lack thereof in the relaxed control ones. Moreover, in the alpha and beta bands, HP is different from most conditions in the frontal lobe (blue dots), which is associated with social interaction. RP also is different from all conditions in this area (green dots), but in the alpha band only.

Fig. 2 C compares the PSD between the three relaxed control conditions. As expected, Vision is different from both Passive and Haptic (light grey dots) in the occipital region for the alpha band (associated with visual processing) as well as in the occipito-parietal area, responsible for motor planning. The latter may be related to the lack of movement in the Vision condition, and hence of haptic and proprioceptive feedback. Interestingly, despite participants remained silent throughout the experiment, we observed differences between control conditions (dark grey and black dots) for the beta band in the temporal region, which is typically associated with speech and auditory signals.

#### B. Haptic interaction with a partner affects brain activity in sensorimotor regions

Fuzzy entropy (Fig. 3 A) is influenced by the experimental conditions in sensory feedback areas (Pz:  $F(6, 3827) = 6.4857, p < 0.0001$ ; POz:  $F(6, 3827) = 14.9499, p < 0.0001$ ). Here, Solo consistently exhibits higher entropy, compared to Passive, Vision and Haptic (all  $p < 0.01$ ), which indicates more complex brain activity. Moreover, Solo also shows higher entropy than RP ( $p = 0.0102$ ) and HP ( $p = 0.0009$ ) in Pz; and than RP ( $p = 0.0434$ ) and TG ( $p = 0.0055$ ) in POz. This could be related to a stronger proprioception and visuo-motor coordination when individuals perform the task alone (i.e., without additional haptic feedback). No differences (at  $p > 0.1$ ) are observed between HP, RP, and TG, suggesting similar complexity among interaction conditions. Accordingly, the order of conditions by higher entropy values in the occipito-parietal area (Solo > RP, TG, HP > Passive, Haptic, Vision) may indicate that sensory information processing is more complex in the Solo condition compared to the interaction conditions, and in these conditions relative to the remaining control conditions that do not require coordination.

Fig. 3, B shows a similar tendency in the motor planning area (Cz:  $F(6, 3827) = 2.1481, p = 0.0451$ ): the interaction conditions are similar (all  $p > 0.03$ ) but exhibit lower

entropy levels than Solo (all  $p < 0.05$ ). As hypothesised the interaction conditions may reduce the complexity of the task through collaboration (H2.2). Conversely, the entropy in this area is highest during the Passive, Vision, and Haptic conditions, where significant differences are observed between these and all three interaction conditions (all  $p < 0.05$ ).

We also investigated the effect of the trial number on the fuzzy entropy metrics, to explore a potential learning-related decrease in cortical signal complexity. In the parietal midline (Pz), we find a significant effect of the trial number ( $F(1, 3827) = 9.174, p = 0.0025$ ) but no interaction between the condition and trial number is observed ( $F(6, 3827) = 1.400, p = 0.210$ ). Instead, in the motor planning area (Cz), both a significant effect of the trial number ( $F(1, 3827) = 6.0482, p = 0.0140$ ) and an interaction effect ( $F(6, 3827) = 2.6079, p = 0.0159$ ) are observed, with a significant negative slope in the HP condition ( $s = -0.0025, p = 0.0086$ ) only, suggesting learning is occurring when participants interact with each other.

The IBS, quantifying the synchronisation of partners' neural activities, (Appendix Fig. 6 C, D) shows a significant effect of the condition for the alpha and beta bands in these regions (Pz in alpha band:  $F(6, 1907) = 2.2454, p = 0.0366$ ; Pz in the beta band:  $F(6, 1907) = 16.2364, p < 0.001$ ). In the beta band, participants exhibit lower synchrony in Haptic, Vision and RP compared to Passive, Solo, HP, and TG (for all pairwise comparisons  $p < 0.02$ ) (Appendix Fig. 6 D). In the alpha band, Solo presents the lowest IBS, although it is only significantly different from Vision and Haptic (both  $p < 0.03$ ) (Appendix Fig. 6 C). This results may indicate that enhanced synchrony in the occipito-parietal region when participants are actively completing the task in a collaborative manner or when both partners are receiving the same visuo-haptic feedback synchronously while being relaxed. Conversely, there are no statistical differences in IBS across conditions in the motor planning area (Cz in alpha band:  $F(6, 1907) = 0.8266, p = 0.5492$ ; Cz in the beta band:  $F(6, 1907) = 0.967, p = 0.446$ ). However, the mean IBS values remain high in HP and low in Solo (Appendix Fig. 6 A, B).

### *C. Synchronicity and activation in social regions is higher with a partner*

Fig. 3 C and Fig. 3 D display the IBS values for the beta frequency band, in the frontal lobe (channels Fz, FP1) and around the right temporo-parietal junction (rTPJ) (channel CP4) respectively, which have been found to be involved in social interaction.

Fig. 3 C shows a significant effect of the condition on the IBS for the beta band in the frontal area (FP1) ( $F(6, 1907) = 15.2198, p < 0.0001$ ), where Solo and Haptic have significantly lower IBS values than all interactive conditions (all  $p < 0.0001$ ). This suggests that partners exhibit higher brain synchrony when they are haptically connected, aligning with hypothesis H2.2. Additionally, we observe that in the Passive condition, IBS values are higher than in Haptic and Solo (both

$p < 0.0001$ ), suggesting that higher synchrony also occurs when partners are relaxed while receiving synchronous sensory feedback. This aligns with the findings presented in Section II.B.

Channel CP4 (Fig. 3 D), also shows a significant effect of the condition ( $F(6, 1907) = 4.7548, p < 0.0001$ ), with IBS during HP being significantly higher than in the Solo, Vision and Haptic conditions, as well as in the other two interaction conditions (all  $p < 0.034$ ). Thus, the neural activities of connected partners exhibit stronger synchronisation, as we hypothesised (H3). Consistent with findings in the frontal area, during the Passive condition, partners' IBS is higher than during the Haptic, Vision, TG and RP conditions (all  $p < 0.0001$ ). Indeed, Passive is the only condition in which participants are relaxed and passively moved by the robotic interface, such that all the sensory feedback modalities investigated are identical for both partners (see Table I). A similar trend is detected when extracting IBS from the alpha frequency band in the social areas, where the synchrony during Passive and HP is generally higher than during the other conditions (Appendix Fig. 7 A B).

Regarding the chronological change of IBS over trials in each condition, we observe a significant effect of the trial number ( $F(1, 1907) = 16.4256, p < 0.0001$ ) and an interaction effect with the condition ( $F(6, 1907) = 6.6793, p < 0.001$ ) in the beta band for the social area (FP1). More specifically, there is a significant positive slope in the RP condition ( $s = 0.0026, p = 0.0012$ ) and a significant negative slope in the TG condition ( $s = -0.0021, p = 0.0091$ ). This suggests that there is increased synchrony over time between participants interacting with a human-like robot partner but not with the more traditional robot assistance.

As for the entropy values in the frontal area (Fz, 6), linked to social interaction, there is an effect of the condition ( $F(6, 3827) = 3.8148, p < 0.001$ ). Here, Solo exhibits the lowest median entropy, although it is not significantly different from the other conditions ( $p > 0.26$ ), except for RP ( $p < 0.03$ ) (Appendix Fig. 7 C). This is likely because no haptic feedback is involved in the Solo condition. Moreover, in the social area (Fz), participants' cortical signals exhibit lower entropy during RP compared to Haptic, Passive and the other two interaction conditions (all  $p < 0.05$ ). In Fz, we also observe an effect of the trial for the fuzzy entropy, with a significant negative slope in the HP condition ( $s = -0.0019, p = 0.0473$ ). These results may indicate that partners learn to use the haptic communication channel more effectively over time, which reduces the complexity of their cortical signals.

## III. DISCUSSION

Although well-understood at the behavioural level, the neural basis of HC remained largely unexplored, as previous EEG hyperscanning studies essentially investigated social interaction without physical connection. Using a dual wrist-robot interface to systematically control these available sensory modalities, this study explored the neural mechanisms of HC

during human-robot and human-human interaction in a target-tracking task.

#### A. Brain regions and frequencies are associated with haptic social interaction

We observed differences between the three interaction conditions and Solo in the left frontal, right motor, and occipito-parietal regions across all frequency bands, which aligns with previous findings comparing haptic and non-haptic conditions during a tracking task [22]. In the midline frontal area, theta oscillations are known to reflect unexpected partner movements and attention to the partner in social interactions [23]–[27], which may explain the stronger oscillations during the interaction conditions. Alpha oscillations in this region are also associated with monitoring a partner's behavior during joint interactions [15], [23], consistent with the differences observed in alpha-PSD of the frontal area between interaction conditions and Solo. Similarly, when humans perceive their partner's movement and consequently adapt their task planning and control, research has shown increases in the theta activity of the occipito-parietal region [23], as well as alpha activity in the occipito-parietal region [23], [28] and the centro-parietal region [11], [29]. The role of alpha oscillations in this context can thus explain the differences in this frequency band in the occipito-parietal area, between Solo and the interaction conditions, and between the relaxed control conditions and the interaction conditions. As hypothesised, we observe that the brain regions and frequency oscillations typically activated during social interaction are also identified here (H1).

Although previous studies on social interaction and interpersonal coordination tasks mainly reported that related neural correlates occur in lower frequency bands, in this study we also found relevant differences between partner and control (alone and relaxed) conditions in the beta band. Typically, suppression in beta oscillations in the motor cortex was found when individuals performed a movement [30]. In our case, this phenomenon is evident in all conditions, although it is more pronounced in the interaction and relaxed control conditions, during which participants received haptic feedback. Indeed, a previous study investigating interaction and motion observation with either a human or robot partner during an object manipulation task without direct HC found stronger suppression in central areas during interaction compared to observation, with no differences human and robot interactions [31]. This aligns with the differences observed between Solo and the interaction conditions in this region, and with the lack thereof among the interaction conditions. Indeed, weaker suppression is observed when individuals conduct the task alone, which indicates that specialised brain regions respond differently depending on the experimental condition (H2). Moreover, in line with our findings, previous studies have highlighted the role of beta oscillations in the central and occipito-parietal regions in facilitating higher-level social processing during dyadic tasks [11], [12]. The similarity between the interaction conditions and the relaxed control conditions can be explained by the strong haptic feedback during the

control conditions given synchronously for both partners in the dyadic setup, suggesting the role of these regions in processing haptic information (H2). However, we did observe differences between the relaxed control conditions and the HP condition in the right frontal area, which is often considered as a key region during social interaction, as previously discussed.

#### B. Brain activity in motor regions is affected by a partner's assistance

We investigated fuzzy entropy, characterising signal complexity, of the cortical activity of the parietal lobe, as it is associated with multisensory integration into humans' motion planning [22], [32]. In this region, the ranking of mean entropy values seems to correspond to the motion state and haptic feedback level, where more task-related feedback was received in interaction conditions than in passive conditions: RP, HP, TG > Passive, Haptic, Vision (H2.3). This may reflect that more complex brain patterns are required to integrate haptic feedback from a partner into one's motion plan, although it occurs concurrently with an increased task performance, as observed in our previous research [1], [2]. More specifically, we found the entropy in the RP condition to be higher than in the two other interaction conditions, while HP exhibited the lowest entropy, suggesting that during the interaction between two human participants, the haptic feedback may be integrated more easily.

Somewhat surprisingly, Solo exhibited the highest entropy in both visuo-motor coordination and motor planning areas, contradicting our initial hypothesis (H2.2). Indeed, previous studies investigating haptic feedback during a visuo-motor task found stronger suppression in motor and parietal regions when haptic feedback was received, indicating increased task-related neural activation [22]. On the other hand, fuzzy entropy characterises the signal in a broader manner and less predictable EEG signal could be observed in the Solo condition since more attention to the reduced sensory information available is needed when performing the task alone.

In the motor planning region, which is associated with the coordination and execution of motor tasks [33], Solo also displayed a higher level of entropy compared to the interaction conditions, potentially reflecting the aforementioned increase in task complexity (H2.2). We did not observe differences in brain complexity in this region among interaction conditions, although, on the behavioural level, a higher error variability was observed when interacting with a HP compared to TG [2]. Contrary to our expectations, brain complexity during HP, which does not always provide assistance, was not higher than in the other interaction conditions. However, we observed a significant decrease in fuzzy entropy over trials during HP in this region, which may indicate adaptation and more efficient integration of the multisensory feedback into participants' motor plans. Interestingly, the control conditions Passive, Haptic, and Vision, where participants were asked to keep their hand relaxed, while it is being moved by the robot, or to track the dot with their eyes only and their hand remains at their resting position, present the highest fuzzy entropy in the

motor planning region among all conditions. This is different from our hypothesis (H2.3), where we expected the signal complexity in this region to be low due to the relaxed state of participants and we were not able to determine the reasons of this result.

We also investigated the IBS metric, used as an EEG feature to assess the strength of the synchronicity between the cortical activity of the two partners during a joint task. In the parietal lobe regions, we found that Solo presented the lowest IBS in the alphaband. This corresponds to our initial hypothesis that when partners are performing the task alone, their activity does not synchronise (H3). On the other hand, higher IBS were observed in the HP, TG and Passive conditions. In the HP condition, this can be explained by the fact that participants exchange forces due to the virtual spring connection, suggesting that they were indeed haptically communicating. However, IBS was also high during the Passive condition although participants were not connected. The design of this condition was such that participants received the exact same visual and haptic feedback from the system in a synchronous manner. This may have led to an increased brain synchronisation, as previously observed in other studies, where two participants listened to the same music [34], watched the same movie [35] or played a video game online [14] and displayed synchronised activity in their motor planning and occipito-parietal regions.

### *C. Synchronicity and activation in social regions is higher with a partner*

We also explored cortical activity synchronisation in the frontal lobe and the rTPJ, thought to be associated with social interaction [16]. More specifically, we looked for a change in the alpha band, which is involved in action-perception coupling [11], [36], and the beta band, associated with co-operative actions (e.g., tasks that require precise control and response) [36]. In both of these areas, IBS was higher when humans were connected to each other compared to when they performed the task alone. Moreover, IBS during Solo was significantly lower than most other conditions (H3), for both beta and alpha bands (Fig. 3C and 3D, Appendix Fig. 7 A, B). This aligns with previous work providing evidence of higher IBS values occurring with a higher rate of cooperation during social interaction [11]. More specifically, IBS in the beta band is associated with cooperative actions [36] and IBS in the alpha band could play a role in processing and integrating the movements of others [6], [17].

However, there was no distinction between the interaction conditions in the IBS of the frontal lobe. We also did not find that IBS in the frontal lobe decreased with the level of human likeness of the haptic communication (HP > RP > TG > Passive > Solo) as initially hypothesised (H2.1). Notably, the Passive condition consistently yielded high IBS in the beta band, in the social areas. This is potentially because, as previously discussed, the two participants consistently received the same stimuli as their targets and haptic feedback were synchronised. This is consistent with similar work that has shown increased IBS in response to the same feedback [37]. In

particular, the higher IBS is observed in the rTPJ when people are watching the same videos [35] and in the frontal lobe when they are listening to music [34]. This can also be observed in the fuzzy entropy results for the frontal lobe, where higher brain complexity is observed in the HP and TG condition but also in the Haptic and Passive conditions. Here, we also found that in the rTPJ, synchronisation in the beta-band was highest in HP compared to all other conditions, including the other interaction conditions (Fig 3.D) (H2.1). This finding is in agreement with previous work, where this region was prominent when participants engaged in social interaction and joint actions [16], [38], [39].

Contrary to expectations, IBS in the frontal region did not decrease in the presence of solely visual stimuli although the hand was maintained at the resting position. This finding may be attributed to social interactions that are purely visual as the synchronisation was previously found even during joint observation of pre-recorded hand movements without direct interaction [11]. Furthermore, lower IBS values in this same region were found in the Haptic condition, suggesting that the elimination of visual stimuli may play a role in social interactions since participants still received the same haptic feedback in this condition. This aligns with previous findings stating that visual cues are important for activating social-related interaction and perception [40], [41].

Additionally, we observed lower brain complexity (i.e., lower fuzzy entropy) in the frontal area during Solo. This further indicates that these networks, used in predicting the mental states of others and understanding their intentions [42], [43], are less exploited when participants conducted the task on their own. In the frontal midline, fuzzy entropy decreased over time in the HP condition, which could suggest that humans adapted their interaction during the joint target tracking task.

## IV. CONCLUSION

The present study investigated the underlying neural mechanisms associated with social haptic communication during a joint target-tracking task using a dual wrist robotic interface and a hyperscanning EEG recording system. The scalp plots and PSD analysis confirmed that cortical activities in the frontal lobe and the occipito-parietal lobe are involved in the processing of haptic social interaction in theta and alpha frequency bands, but also in the beta band. In the regions associated with motor planning and multisensory integration, we observed higher fuzzy entropy in the relaxed conditions with strong haptic feedback compared to the interactive partner conditions. Inter-brain synchronisation in these areas was lowest when participants completed the task on their own, and remained high in all other conditions, even when they were asked to relax while the robot moved their hand. We think this may be due to the experimental design, where synchronous visual and haptic feedback was provided to both participants. Regarding areas involved in the processing of social interaction, similar trends are observed where IBS was stronger in the interaction conditions than in Solo both in the alpha and beta bands, although it was also high in the

Passive condition. When investigating the difference between the human partner condition and the robot interaction ones, we found a stronger IBS around the rTPJ when humans were connected to each other, while other findings did not provide clear distinctions. Further exploration of brain synchronisation mechanisms, particularly with different levels of human-like algorithms and non-synchronised tasks is necessary to deepen the understanding of haptic social interactions.

## V. METHODS

### A. Participants

This study was approved by the Research Ethics Committee of Imperial College London (reference number: 21IC6578) and adhered to all relevant ethical and data protection regulations. A total of 24 right-handed individuals without known impairments participated in the study, forming twelve dyads. The participants, evenly split between males and females, had an average age of  $23.6 \pm 1.4$  years.

### B. Experimental setup

The experiments were conducted using the Hi5 dual robotic interface [7], with each member of the dyad seated in front of an individual monitor (Fig. 1). Participants placed their right arm in an individual wrist robot, which applied computer-controlled torque during movement. The two dyad members performed the same target-tracking task on separate monitors by executing wrist flexion/extension motions. Separated by a curtain, they were unable to communicate during the experiment and not aware of the partner's task. They were instructed to 'follow the target as accurately as possible' and were informed that they might feel some forces during the task.

The target to be tracked followed a pseudo-random multi-sine function

$$q^*(t) = 18.51 \sin(2.031t) \sin(1.093t), \quad 0 \leq t \leq 15 \text{ s} \quad (1)$$

where  $q^*(t)$  represents the desired target position at time  $t$ . Haptic feedback during motion consisted in a spring torque (in Nm)

$$\tau(t) = K [q_r(t) - q(t)], \quad (2)$$

where  $q(t)$  is the wrist angle in degrees and stiffness  $K$  is in Nm/deg. Three types of connections were implemented, with  $q_r(t)$  as (i) the target trajectory in the *trajectory guidance* (TG) condition, (ii) the partner's wrist angle in the *human partner* (HP) condition, and (iii) the output of a human-like interactive control algorithm of [3] in the *robot partner* (RP) condition.

Cortical activity was recorded for both participants in each dyad, was recorded from 2\*64 EEG channels using the 10-10 international positioning system through Ag/AgCl active electrodes (waveguard cap ANTneuro, Netherlands), and with two eego mylab amplifiers (ANTneuro, Netherlands). CPz was used as the reference electrode and AFz as the ground electrode, and the electrode impedances were kept below  $10\text{k}\Omega$ . The software eemagine (eemagine Medical Imaging Solutions GmbH, Germany) was used to acquire and save the data, sampled at a frequency of 500Hz.

TABLE II: Parameters for different conditions.

Condition	Stiffness Nm/ $^\circ$	Participant's behaviour	Haptic feedback
Solo	0	active	no
Vision	-	relaxed	no
Haptic	0.2967	relaxed	high
Passive	0.2967	relaxed	high
Robot Partner (RP)	0.0498	interactive	medium
Human Partner (HP)	0.0498	interactive	medium
Trajectory Guidance (TG)	0.0498	relaxed or interactive	medium

### C. Experimental conditions

Table II summarizes the seven conditions used during the experiment. In the Solo condition, participants tracked the target on the screen using only visual information, with the robot's motors turned off. In the Passive condition, the wrist was guided along the target trajectory via a rigid connection with high stiffness, while participants were instructed to relax their arms (i.e., they received visual and haptic feedback). In the Vision condition, participants did not move their wrists but received visual stimuli of the moving target on their monitor (i.e., they only received visual feedback). In the Haptic condition, the wrist was guided along the target trajectory, as during the passive condition, but without visual feedback on the monitor (i.e., they only received haptic feedback). For each of the {TG, HP, RP} conditions, the stiffness was set to  $0.0498 \text{ Nm}/^\circ$  in Eq. 2, and each dyad member received visual feedback of the common target and of their own cursor on their individual monitor. In these three conditions, they therefore received both visual and haptic feedback. The connection stiffness for the interaction conditions was  $0.0297 \text{ Nm}/^\circ$  and for Haptic and Passive  $0.2967 \text{ Nm}/^\circ$ . Each condition consisted of 23 trials, each lasting 15 s, tested in blocks. The experiment always started with the Solo condition as the first block, followed by the three interaction conditions (TG, HP, RP), with the sequence randomised for each dyad. The three control conditions were consistently placed at the end of the experiment in the same order – Passive, Vision, Haptic.

### D. Frequency and channel selection for haptic communication in PSD, fuzzy entropy and IBS analyses

Neural oscillation frequencies in different cortical areas are modulated relative to the task being performed. This modulation has been widely observed across a broad range of experiments investigating perception [44]–[46], attention [47]–[49], decision-making [50], [51], and movement [52]–[54]. The majority of cortical activity is typically recorded in the delta, theta, alpha, and beta frequency bands in EEG [55]. In this study, we focused our analysis on the theta, alpha, and beta frequency bands, as hardware noise may have affected delta wave recordings. For the analysis of fuzzy entropy and inter-brain synchrony (IBS), we focused on areas associated with social interaction, motor planning, and haptic feedback, which were identified based on prior research.

The central prefrontal cortex (Fpz, AFz) has been shown to play a crucial role in social cognition, particularly in

integrating environmental information into motor control processes [56]. To target the motor planning region, electrodes Cz, C3, and C4 were selected due to their proximity to the central lobe [57]. The primary motor cortex (M1 [58]) is responsible for detecting body movement and muscle activity, which is relevant to our tracking task, where we focused on left hemisphere electrodes, given that participants used their right hand. For haptic feedback processing, we included electrodes near the primary and secondary somatosensory cortex (S1 and S2) — namely, Pz, P3, P4, CPz, CP3, and CP4 — due to their location in the parietal and central-parietal regions [22]. These regions are closely associated with the processing of tactile information such as touch, proprioception, and pressure [59].

Additionally, IBS has been found to increase during social interaction tasks, particularly in the prefrontal cortex [60] and the right centro-parietal area in the alpha band [11], [12], [55], as well as the beta band near the right centro-parietal area and right occipital lobe [13]. Therefore, for our fuzzy entropy and IBS analysis, we focused on four key channels: Fpz (prefrontal cortex) and CPz (central-parietal lobe) for social interactions, Cz (central lobe) for motor planning, and Pz (parietal lobe) for haptic feedback. Our investigation concentrated on the alpha and beta frequency bands.

TABLE III: Brain areas related to social haptic interaction.

Network function	Brain regions	Brain areas	Electrode
social interaction	prefrontal, right centro-parietal	pSTS, PFC	Fpz, Cp4
motor planning	premotor, motor, somatosensory cortex	PMC, CMA, SMA, SPL	Cpz, Cz
haptic feedback	parietal lobe	S1, S2	Pz

#### E. EEG pre-processing

The pre-processing steps based on EEGLAB [61] for the EEG data are outlined in Fig. 4, with detailed descriptions for each step provided in the Appendix. Independent Component Analysis (ICA) [62] was used to remove signal artifacts, primarily caused by blinking, muscle activity, and heartbeat. ICLabel classifiers were employed to determine whether these artifacts were from brain components, allowing the preservation of the original cortical data as much as possible. The TBT toolbox [63] in Matlab was then used to assess the quality of each EEG channel in each trial, replacing excessively noisy channels with the average of the surrounding channels to avoid significant data loss. Finally, the Current Source Density (CSD) algorithm [64] was applied to enhance the spatial resolution of the EEG data, sharpening the final scalp image (Fig. 2) and improving the visualization of the signal source location.

#### F. Metric extraction

Scalp topographies were plotted for each condition using ICA and frequency decomposition, with various metrics extracted from the EEG data for each channel and trial.

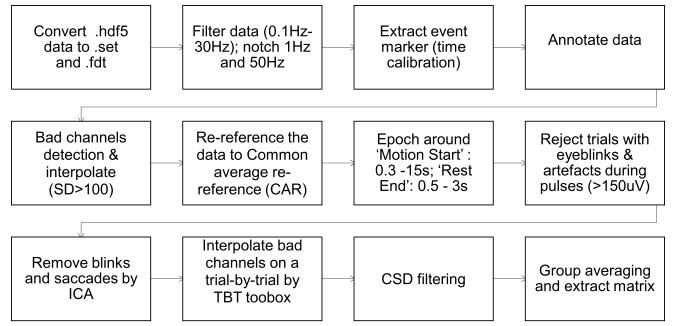


Fig. 4: EEG pre-processing pipeline.

EEG oscillations, which reflect cognitive processing, were analyzed using Welch's power spectral density (PSD) estimation. PSD was computed across 61 channels, focusing on three frequency bands relevant to human coordination (HC) [65], [66]: 5-7 Hz, 8-13 Hz, and 13-29 Hz. To reduce noise, a time window of 1.0 seconds with a 50% overlap was applied.

We also computed fuzzy entropy to capture the complexity of EEG signals, as it is sensitive to the dynamics of brain activity and robust to noise [18]–[20], [67]. Higher fuzzy entropy values suggest more complex, less predictable brain patterns, often reflecting heightened cognitive engagement. This measure has proven effective in decoding EEG signals during imagined hand movements [68] and in comparing brain states across conditions [69], [70]. Our method for computing fuzzy entropy is based on Tong's work [67], which shows its superiority over sample and approximate entropy for physiological signal analysis.

Additionally, we calculated IBS, commonly used in hyperscanning studies to assess neural synchronization during social or collaborative tasks [13], [14], [17]. IBS reflects the alignment of neural activity between individuals, associated with shared attention and communication efficiency. We used the method by Hu et al. [71], which incorporates wavelet transformation to select relevant frequencies and time intervals. Traditional techniques like correlation and coherence were also applied to estimate the rate of interbrain synchronization.

#### G. Statistical Analysis

In this work, we addressed how each metric changes throughout trials and is affected by the different experimental conditions. For each metric, we fitted a linear mixed-effects model (LME) via restricted maximum likelihood. For the fuzzy entropy and PSD metrics, the trial number and the condition type were included as fixed effects (slope), and the subject ID and dyad number as random effects (intercept), with the subject ID nested into the dyad number. For the IBS, the trial number and the condition type were included as fixed effects (slope), and the subject ID as a random intercept. From each extracted model, we conducted post-hoc tests using estimated marginal means (or least-square means) for the experimental conditions. The corresponding contrasts

and interaction contracts were calculated to obtain pairwise comparisons across the conditions. The false-discovery rate correction was applied to adjust p-values and control for Type I error in multiple comparisons. The statistical analysis was performed in R.

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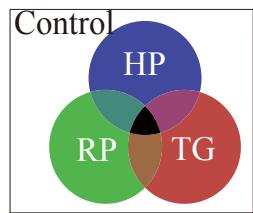
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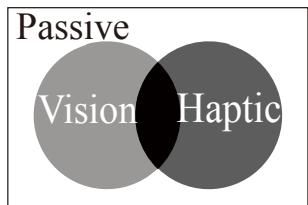
COLOUR CODE FOR FIGURE 2 B AND C

A



- TG ≠ Solo & TG ≠ RP & TG ≠ HP & HP=solo & RP=solo
- RP ≠ Solo & RP ≠ HP & RP ≠ TG & HP=solo & TG=solo
- HP ≠ Solo & HP ≠ RP & HP ≠ TG & RP=solo & TG=solo
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- TG ≠ Solo & RP ≠ solo & TG = RP & HP = solo & TG ≠ HP & RP ≠ HP
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- RP ≠ Solo & HP ≠ solo & TG ≠ solo & HP=TG & HP=RP & RP=TG

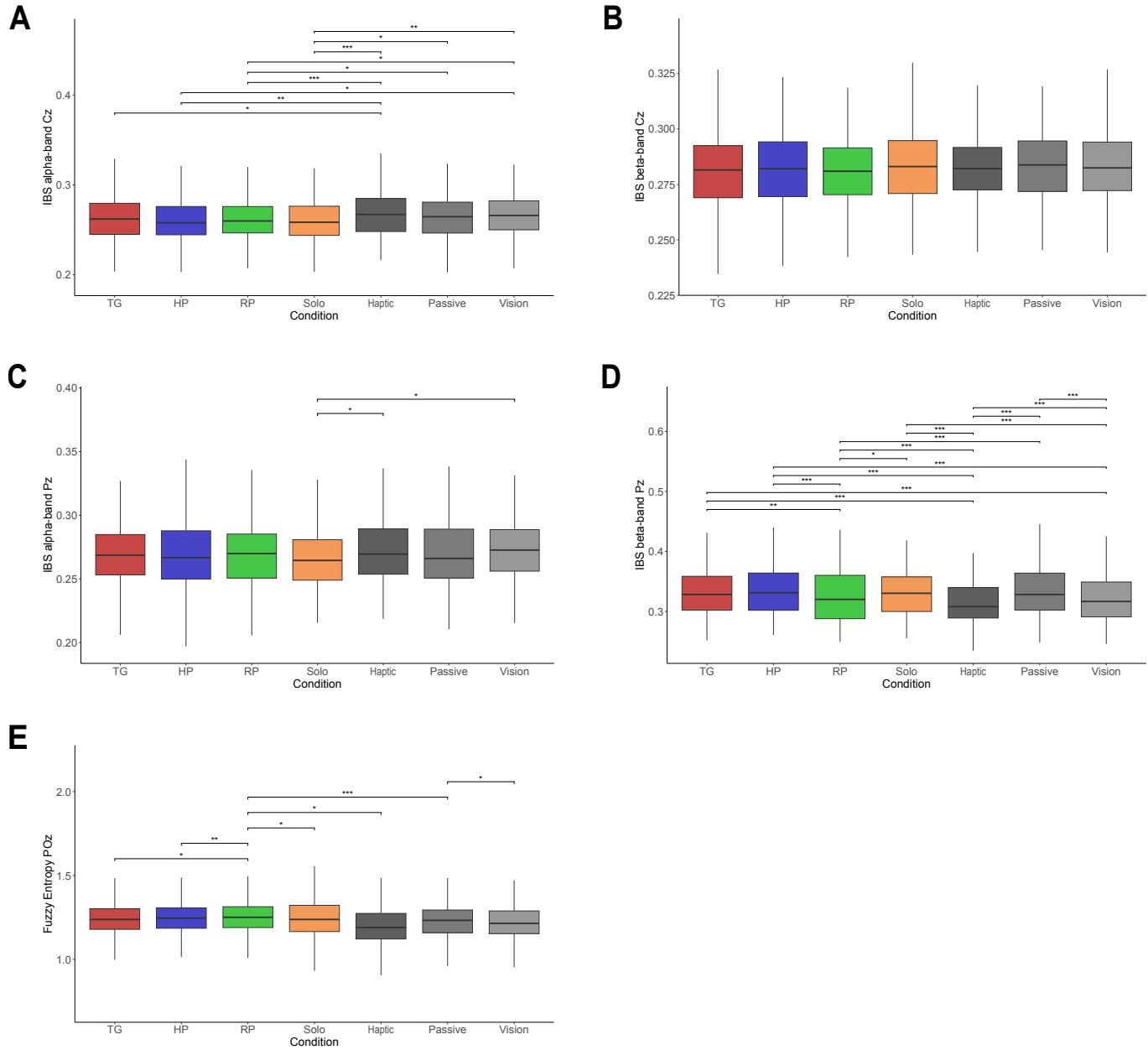
B



- Haptic ≠ PTG & Vision=PTG & Haptic ≠ Vision
- Vision ≠ PTG & Hand=PTG & Haptic ≠ Vision
- Vision ≠ PTG & Haptic ≠ PTG & Haptic = Vision

Fig. 5: Colour legend for Figure 2 B and C.

**ADDITIONAL FIGURES: HAPTIC INTERACTION WITH A PARTNER AFFECTS BRAIN ACTIVITY IN SENSORIMOTOR REGIONS**



**Fig. 6:** (A) Alpha-band inter-brain synchrony at the Cz channel. (B) Beta-band inter-brain synchrony at the Cz channel. (C) Alpha-band onter-brain synchrony of the Pz channel. (D) Beta band inter-brain synchrony of the Pz channel. (E) Fuzzy entropy at the POz channel.

**ADDITIONAL FIGURES: SYNCHRONICITY AND ACTIVATION  
IN SOCIAL REGIONS IS HIGHER WITH A PARTNER**

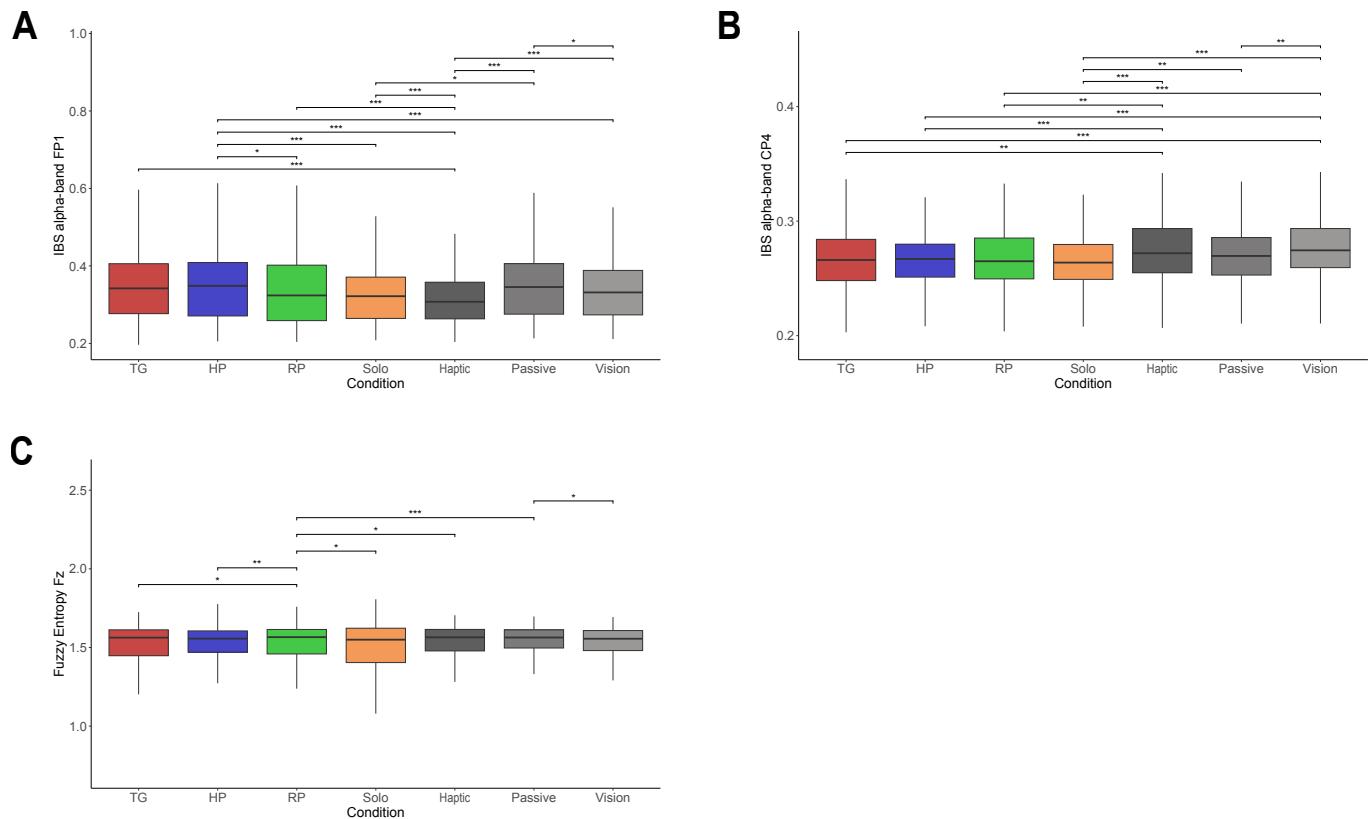


Fig. 7: (A) Alpha-band inter-brain synchrony at the FP1 channel. (B) Alpha-band inter-brain synchrony at the CP4 channel. (C) Fuzzy entropy at the Fz channel.