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Distinct neural dynamics in joint versus side-by-side actions: insights from dual EEG

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Abstract

The distinction between acting jointly and acting side-by-side permeates our daily lives and is crucial for understanding the evolution and development of human sociality. While acting in parallel involves agents pursuing individual goals, acting jointly requires them to share a collective goal. We used dual EEG to investigate neural dynamics underlying these action types. We recorded event-related potentials (ERPs) from 20 dyads while they had to transport an object in a video game, either jointly or in parallel. Conditions were matched for task execution complexity, confirmed by equal success rates. Results revealed a distinctive pattern swap in ERPs during action preparation. Early preparation showed significantly higher amplitude during joint versus parallel action. This pattern reversed in late preparation, with significantly reduced ERP amplitude in joint compared to parallel action. Notably, decreased late ERPs correlated with higher RT variability in partners but not participants' own RT variability. This dynamic swap suggests different cognitive processes operate at distinct stages of action preparation. Sharing a collective goal may impose cognitive costs (reflected in higher early ERPs), but this is offset by facilitated late action preparation (as shown by reduced late ERPs), likely due to the enhanced predictability of partners' actions.

Keywords: joint action; parallel action; collective goal; action preparation; dual EEG

Introduction

Anyone who has ever danced a tango or cooked a hollandaise sauce knows that acting jointly differs from merely acting side-by-side. This distinction pervades our daily experiences (Gilbert 1990, Bratman 1993) and marks a pivotal step in human social evolution (Tomasello et al. 2005) and development (Carpenter 2009, Brownell 2013), as also evidenced by children's early ability to distinguish between joint and parallel actions when observed (Begus et al. 2020, Vizmathy et al. 2024).

Over the last two decades, research has extensively investigated the processes underlying joint action (Sebanz and Knoblich 2021). Studies consistently show that agents represent others' actions (Loehr et al. 2013, Meyer et al. 2013, Kourtis et al. 2014, 2019, Novembre et al. 2014, Satta et al. 2017, Sacheli et al. 2018) and synchronize (Repp and Su 2013, Keller et al. 2014, D'Ausilio et al. 2015, Pezzulo et al. 2022, Bigand et al. 2024) during shared activities like clinking glasses, playing music, or dancing. Similar results have been obtained in monkeys (Ferrari-Toniolo et al. 2019, Lacal et al. 2022, Pezzulo et al. 2022). Moreover, there is evidence that sharing task representations affects joint action performance (Schmitz et al. 2017, 2018). Other studies point to temporal adaptation, the speeding up or slowing down of individual actions to match observed behaviour (Konvalinka et al. 2010, Nowicki et al. 2013, Lelonkiewicz and Gambi 2017).

However, others' action representation and synchronization also occur when acting individually. People often represent others' actions even when it impairs their performance (Atmaca et al. 2008, 2011), and agents share task representation also when they are not required to act jointly (Sebanz et al. 2003). While synchronization can facilitate interpersonal coordination (Nessler and Gilliland 2009, Richardson et al. 2007), it can occur unintentionally (Varlet et al. 2015) and persist despite attempts to avoid it (Issartel et al. 2007, van Ultzen et al. 2008).

All these findings indicate that the distinction between joint and parallel action remains underinvestigated. Our paper aimed to bridge this gap. We used dual electroencephalography (EEG) to record brain activity from two individuals simultaneously, exploring the neural dynamics that distinguish joint from parallel action.

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Joint action is minimally characterized by a collective goal rather than the individual goals driving parallel action (Searle 1990; Gilbert 2013; Bratman 2014). Instead of simply comparing solo and dyadic actions, as previous studies have done (but see della Gatta et al. 2017, Barchiesi et al. 2022, Formica and Brass 2024), we contrasted two-agent actions directed towards either collective or individual goals while matching the tasks for movement and coordination complexity.

Participants in dyads played a video game in which they controlled cursors to navigate a path and transport shovels into an igloo. In the Joint Action condition, two players moved one shovel *together*; in the Parallel Action condition, each player transported their shovel *individually* alongside the other. In both conditions, players should monitor their partner's cursor movements. In the Joint condition, the action's outcome depended on the successful performance of both players. In contrast, in the Parallel condition, each agent pursued their individual goal independently while avoiding collisions with the other.

We focused on the behavioural and electrophysiological differences between joint and parallel action preparation. At the behavioural level, we considered the success rate to evaluate task complexity across conditions and analysed mutual alignment within participant dyads by measuring the association between their reaction times and reaction time variability. We used a cluster-based permutation analysis at the electrophysiological level to identify differences in event-related potential (ERP) amplitude between the Joint and Parallel conditions across all electrodes during the action preparation phase. Finally, we bridged the behavioural and electrophysiological levels by exploring whether differences in ERP amplitude across conditions correlated with changes in self- and partner-related reaction times and their variability.

If sharing a collective goal provides a core definition of joint action, it should manifest in different behavioural patterns and neural dynamics compared to parallel action. Sharing a collective goal rather than pursuing individual goals should impact on the various stages of action preparation, even when the tasks match in complexity.

Materials and methods

Participants

Twenty dyads of right-handed participants ($n = 40$, 20 females, mean age 24.1) were recruited for the experiment. All participants had normal or corrected-to-normal vision and no history of psychiatric or neurological disorders. The research protocol was approved by the Local Ethics Committee and was conducted in accordance with the principles of the revised Declaration of Helsinki (World Medical Association General Assembly 2008). Written informed consent was obtained from all the participants. To calculate the sample size, we ran a power analysis based on the modulations of contingent negative variation in a joint task reported by Kourtis et al. (2019). Although there are consistent differences in the data analysis, their task provides the most similar paradigm. This analysis was carried out with MorePower and showed that 16 dyads, i.e. 32 participants, were sufficient to replicate the effect they observed (Experimental design: 2 × 2×2 repeated measures ANOVA; effect of interest: 2 (Joint/no Joint); Power: 0.80; Partial Eta^2: .219; calculated sample size: 32 participants).

Experimental setting

Participants were randomly paired in dyads (e.g. five male/male, five female/female, and ten male/female) and seated side-by-side at desks in an electrically shielded chamber (a Faraday cage), 150 cm apart. Each participant faced their computer screen (ASUS VG248QE, 61 cm × 34.4 cm, 60 Hz refresh rate, 1920 × 1080 resolution) positioned 50 cm away. The task was a cartoon-like video game, adapted from Satta et al. (2017), programmed in Psychtoolbox-3 on MATLAB R2023b (The MathWorks Inc., Natick, MA, USA). A single PC drove both displays, and each participant controlled their actions using a Saitek X65 F Control System isometric joystick with their right hand.

EEG was recorded simultaneously from both participants using a g. HIamp amplifier (g.tec medical engineering GmbH, Schiedlberg, Austria). Data were acquired at 1200 Hz using two 64-electrode caps following the 10–20 system. The reference electrode was placed at FPz, and the ground electrode was placed at the nose tip.

Task

Participants controlled cursor characters (puppets) with a height of three degrees of visual angle (DVA), using joystick force pulses to move from the centre in different directions. Characters were identical, except for their clothing colour: red for the left participant and green for the right (see Fig. 1a). The task required participants to navigate their characters, pick up a shovel, and transport it into an igloo along a predetermined path. The experiment included two conditions: in *Joint Action* (JA), participants jointly transported a single shovel, while in *Parallel Action* (PA), each participant independently transported their own shovel alongside the other.

Each trial began with a black fixation cross on a white background, which remained for 2000 ms. Participants were then presented with the red and green characters and a central circle. They were asked to position their character inside the circle and hold their cursor still to maintain the character within it for a variable time interval (centre holding time, CHT), lasting from 1000 to 2000 ms in 100 ms increments. Any cursor displacement outside the target resulted in an error and consequent abortion of the trial. Then, an instruction cue was presented for 1500 ms, corresponding to the action preparation phase, followed by a go-signal, upon which participants moved as fast and accurately as possible.

In the JA condition, the cue was a white snow shovel positioned at the beginning of a ground path extending from the centre to a white igloo (9 × 5 DVA), appearing as a peripheral target at one of four random positions (11 DVA eccentricity from the screen centre). The go-signal consisted of the shovel changing colour from white to red and green. Both participants then moved to grab and transport the shovel *jointly* towards the igloo, maintaining coordination by staying within the marked path and keeping their inter-cursor distance under 150 pixels. Success triggered a snow removal animation and changed the igloo's colour to red and green. The trial ended unsuccessfully, leaving the igloo white if either participant anticipated the go-signal, left the path, or exceeded the allowed distance from their partner. The trial outcome depended on the joint performance of both participants.

The PA condition followed a similar structure but with two key differences: (i) two shovels appeared instead of one, and (ii) participants acted independently. At cue onset, two white shovels appeared on the path. At the go-signal, these shovels changed colour (left to red, right to green), matching each participant's character colour. Participants were informed about the shovel positions and colour changes, enabling them to plan their movements during the preparation phase. After receiving the go-signal, each participant had to reach for their shovel and *individually* transport it to the igloo without leaving the path. To prevent a collision, participants followed priority rules: the red player had priority in the left half of the path, while the green player had priority in the right half. Overlapping positions (within 50 pixels) in the same path half resulted in trial failure for the player without priority. Unlike in JA, individual errors (anticipating the go-signal, leaving the path, violating priority rules) affected only the participant who made them. Participants were carefully instructed that their actions were side by side, neither competitive (i.e. the order of arrival at the igloo was irrelevant) nor cooperative (i.e. avoiding systematic taking turns in action execution to prevent collisions). Success was also tracked individually: the igloo changed colour partially (red or green) for each successful participant or entirely for concurrent success and remained white if both participants failed. For trial structure visualization in both conditions see Fig. 1b. The movies for the two tasks are available at the following link.

Participants completed eight blocks of 48 trials each (384 total trials, 192 per condition), with 12 repetitions for each of the four target directions (up-left, up-right, down-left, down-right). JA and PA blocks alternated, with starting conditions counterbalanced across dyads. Before the experiment, each dyad completed two training blocks of 16 trials each (4 directions × 4 repetitions), following their assigned experimental order (JA-PA or PA-JA). Training trials were excluded from the analysis. All procedures were administered via Psychtoolbox-3 in MATLAB 2021b.

Behavioural data analysis

Trials were included in the analyses only if they presented a clear post-go movement onset, defined as the first velocity peak after the go-signal exceeding two mean absolute deviations above the median velocity in the action preparation phase. In this way, we excluded both trials with no responses and trials in which excessive movement activity was detected during the preparation phase.

On the remaining trials, we calculated the success rate (SR) as the percentage of trials in which participants successfully reached the igloo, the reaction times (RTs) as the average interval between go-signal and movement onset, and the reaction time variability (RTvar) as the mean standard deviation of RTs across trials. These variables were analysed separately in 2 × 2 mixed ANOVAs, with the within-subject factor 'Condition' (JA, PA) and the between-subject factor 'Player' (Red, Green). The latter factor was considered to ensure that the players' positions did not affect their performance.

Moreover, we conducted an exploratory analysis of dyadic performance to examine behavioural alignment within pairs of participants. We analysed the linear relationship between players' RT and RTvar by calculating correlations between paired participants across all 20 dyads, including one point per dyad. We specifically tested for positive correlations, indicating alignment, as negative correlations would indicate a lack thereof. To quantify how changes in behavioural performance between JA and PA conditions correlated within dyads, we computed the normalized difference ((JA−PA)/(JA+PA)) for both mean reaction time (ΔRT) and reaction time variability (ΔRTvar) for each participant. Then, we separately calculated correlations of ΔRT and ΔRTvar between paired participants across all 20 dyads.

Analyses were run using Jamovi 2.3.24 and JASP 0.18.3.0.

ERP analysis

ERP data preprocessing. Data were preprocessed using EEGLAB (version 2023.1), implemented in MATLAB 2023b. First, continuous data were epoched into 8-second segments (−2000 to 6000 ms relative to the instruction cue), baseline-corrected using the pre-stimulus period, downsampled to 600 Hz, linearly detrended, and low-pass filtered at 30 Hz (using an FIR filter with default settings). After visual inspection, bad channels were interpolated (mean ± sd: 0.9 ± 0.8 channels), and data were average-referenced. Trials with excessive artifacts were removed upon visual inspection, followed by ICA decomposition (RUNICA with default settings). After removing components that had been visually identified as ocular artifacts (mean ± sd: 3.3 ± 0.9 components), trials were re-epoched in 2500 ms segments, starting from 500 ms before the visual cue and ending 500 ms after the go-signal. These epochs were baseline-corrected to 500 ms before the visual cue. A second trial rejection was then performed to eliminate remaining bad trials and trials in which no clear movement onset had been detected (mean number of trials included ± sd: 112.25 ± 31 for JA and 131 ± 24 for PA). Finally, the signal was averaged across trials.

Cluster-based permutation analysis. To investigate the differences in ERPs between JA and PA conditions during the entire action preparation phase, we performed a cluster-based analysis as implemented in FieldTrip (Maris and Oostenveld 2007, Oostenveld et al. 2011). First, we conducted dependent sample *t*-tests (df = 39) to examine differences in ERP amplitudes between the JA and PA

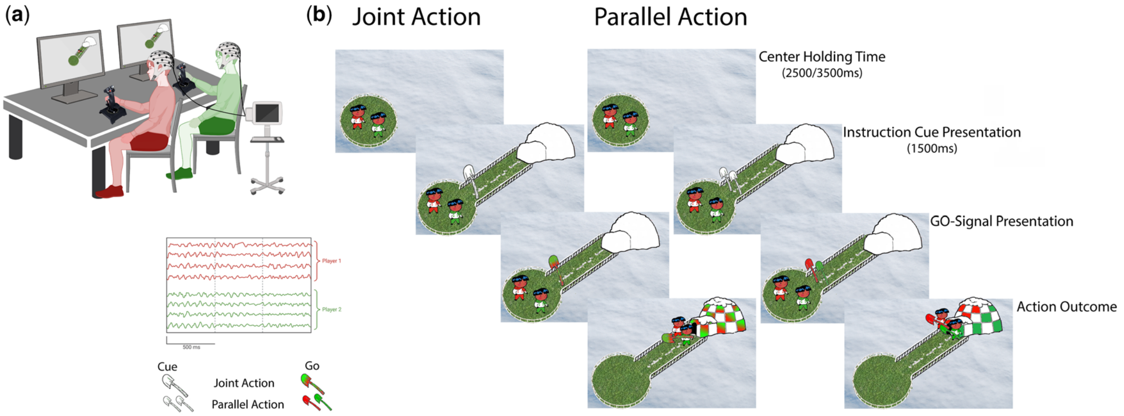

Figure 1. (a) Experimental Setup: During the task, the two participants controlled a red character (on the left) or a green character (on the right) on their screens, using isometric joysticks, while their EEG activity was recorded simultaneously from the same amplifier. The EEG activity of interest consisted of a 1500 ms time window associated with the action preparation phase. (b) Structure of a trial: JA and PA were matched for visual stimuli and task complexity but differed in action outcome. During JA, participants achieved a collective goal by acting jointly with their partner, while during PA, they pursued an individual goal, acting merely side-by-side with their partner.

conditions. These comparisons were performed across all electrodes and time samples within the 1500 ms interval between the visual and go cues. Clusters were formed by two-tailed *t*-values with a *P*-value < .05, considering adjacent time samples and neighbouring electrodes ($n \geq 2$), as defined with default triangulation parameters. To assess significance, the summed *t*-value of each cluster (cluster statistic = maxsum) was compared with the distribution of clusters obtained through permutation testing. Using the Monte Carlo method, ERPs were randomly assigned to either the JA or PA condition 1000 times. The permutation test was two-tailed, and clusters were deemed significant if fewer than 5% of the summed *t*-values from the permutations exceeded the original cluster *t*-value (*P*-value < .05).

Correlations between task-related changes in ERPs and behaviour. We finally explored the potential correlations between ERPs and behavioural outcomes. In doing this, we considered the ERPs during action preparation and calculated the point-by-point difference between JA and PA with the formula (JA–PA)/(JA+PA). This resulted in a time-resolved normalized ERP amplitude difference (ΔERP). Then, we tested the association between ΔERP and changes in partner and self-behaviour between JA and PA, specifically ΔRT and ΔRTvar, using separate cluster-based correlations. Each correlation (df = 38) included ΔERP across all electrodes and time points within the 1500 ms interval between the instruction and go cues, as well as one of the four behavioural variables indicated previously, which remained constant for each time point and electrode. Then, clusters were formed using two-tailed *t*-values with a *P*-value < .05, considering channel neighbours ($n \geq 2$) defined by a triangulation-based layout and adjacent time points. The statistical significance of clusters was determined via a Monte Carlo method with 1000 randomizations, using summed *t*-values as the cluster statistic (=maxsum). Clusters were considered significant for *P*-value < .05.

Considering that this normalization is impacted when conditions' values are close to zero, leading to issues with dividing by small numbers, we controlled the percentage of denominator values smaller than 0.1 in the significant clusters.

Results

Behavioural results

We found no significant differences in SR between JA and PA conditions ($F_{(1, 38)} = 0.136$, $P = .577$, $p\eta^2 = 0.008$; JA: M = 0.897, SD = 0.081; PA: M = 0.903, SD = 0.048; see Fig 2a). The factor player (Red/Green) showed no main effect ($P = .356$) or interaction with Condition ($P = .503$), indicating that seating position did not affect performance.

Mean RTs were significantly higher in PA than in JA condition ($F_{(1, 38)} = 42.924$, $P < .001$, $p\eta^2 = 0.530$; JA: M = 0.329, SD = 0.062; PA: M = 0.406, SD = 0.089; see Fig. 2b). The factor player showed no main effect or interaction with Condition for either mean RTs (main effect: $P = .496$; interaction: $P = .949$).

Similar to RTs, RTvar was greater in PA than in JA condition ($F_{(1, 38)} = 29.801$, $P < .001$, $p\eta^2 = 0.440$; JA: M = 0.173, SD = 0.040; PA: M = 0.247, SD = 0.089; Fig. 2c), with no effect of the player factor (main effect: $P = .752$; interaction: $P = .295$).

RTs were correlated between paired participants across all 20 dyads in the JA [$r(18) = 0.43$, $P = .03$] and PA [$r(18) = 0.42$, $P = .03$] conditions. This result indicated that participants adjusted their RTs to match those of their partner. Specifically, participants tended to respond slowly when their partner's responses were slow; conversely, when their partner's responses were fast, they tended to respond quickly.

RTvars were also positively correlated in JA [$r(18) = 0.47$, $P = .02$] and PA [$r(18) = 0.40$, $P = .04$], indicating that variability in initiating movements was adjusted to match the partner's response pattern (Fig. 2d and 2e).

Finally, behavioural performance changes between the JA and PA conditions correlated within dyads. Precisely, changes in ΔRTvar for the two partners matched, so greater RTvar in PA than in JA in one player tended to correspond to greater RTvar in PA than in JA in their partner [$r(18) = 0.46$, $P = .02$]. No significant correlation was found for ΔRT [$r(18) = 0.19$, $P = .21$] (Fig. 2f).

ERP results

JA and PA conditions differed significantly around two time windows, with a reversed pattern. A first, early difference revealed a

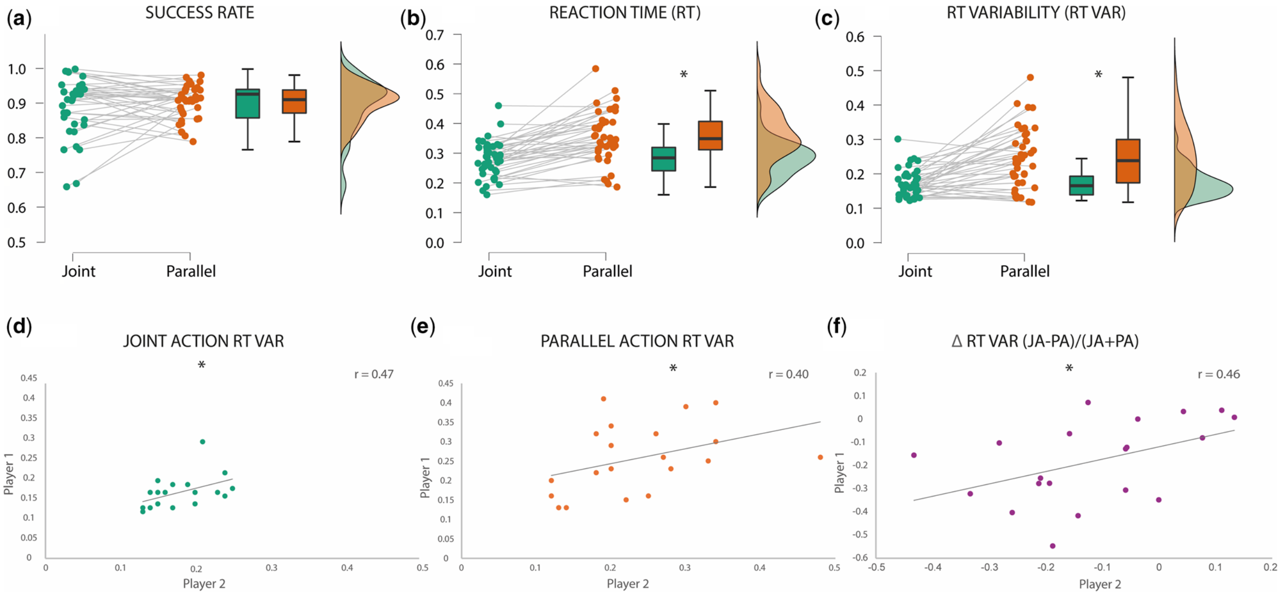

Figure 2. Behavioural results. The top panels show the significant differences between JA and PA conditions in (a) success rate, (b) reaction times, and (c) reaction time variability. Each panel shows individual participants' performance on the left, boxplots in the middle, and density distribution on the right. The bottom panels show significant correlations in reaction time variability across pairs of players. Here, each dot represents the performance of the two players of the couple. Specifically, (d) shows the correlation in the JA condition, (e) shows the correlation in the PA condition, and (f) shows the correlation of ΔRTvar. * P-value < .05

higher ERP amplitude in the JA compared to the PA condition. This was evident as enhanced negativity in a fronto-central cluster of electrodes ($P = .002$; time: from −1.250 to −0.882 ms) and enhanced positivity in JA compared to PA in an occipito-parietal cluster ($P = .004$; time: from −1.261 to −0.898 ms). A second, late difference revealed a smaller ERP amplitude in the JA compared to the PA condition. Accordingly, we found significantly reduced negativity in central-parietal channels ($P = .002$; time: from −0.883 to 0 ms) and reduced positivity in fronto-lateral channels ($P = .002$; time: from −0.820 to 0 ms) during JA compared to the PA condition. Although the time intervals for significant clusters should not be considered as exact latencies in cluster-based analyses (Sassenhagen and Draschkow 2019), these results clearly show a reverse pattern over two distinct time windows (Fig. 3).

Correlations between task-related changes in ERP activity and behaviour

Correlations between ERPs and behavioural outcomes revealed no significant relationship between ΔERPs and changes in self-behavioural performance, ΔRT, and ΔRTvar ($P > .05$). Interestingly, we found a cluster of significant correlations between ΔERPs and partner's ΔRTvar (clusters: $P = .036$ from −0.448 to −0.402 ms; see Fig. 4) and two clusters suggesting a trend in the same direction ($P = .068$ from −0.053 to 0.018 ms; $P = .082$ from −0.387 to −0.350 ms). All these clusters occurred in the late part of the preparation phase. They included frontocentral channels, indicating that a stronger increase in negative ERP amplitude in PA compared to JA was associated with a greater increase in variability of movement initiation in PA than in JA. The control analyses supported that small denominators do not drive these results, as less than 0.1% of denominators were smaller than 0.1 μV in each cluster. No significant correlation was found for ΔRT.

Discussion

The main aim of our paper was to investigate behavioural patterns and neural dynamics that distinguish joint from parallel action preparation. We analysed mutual alignment measured by

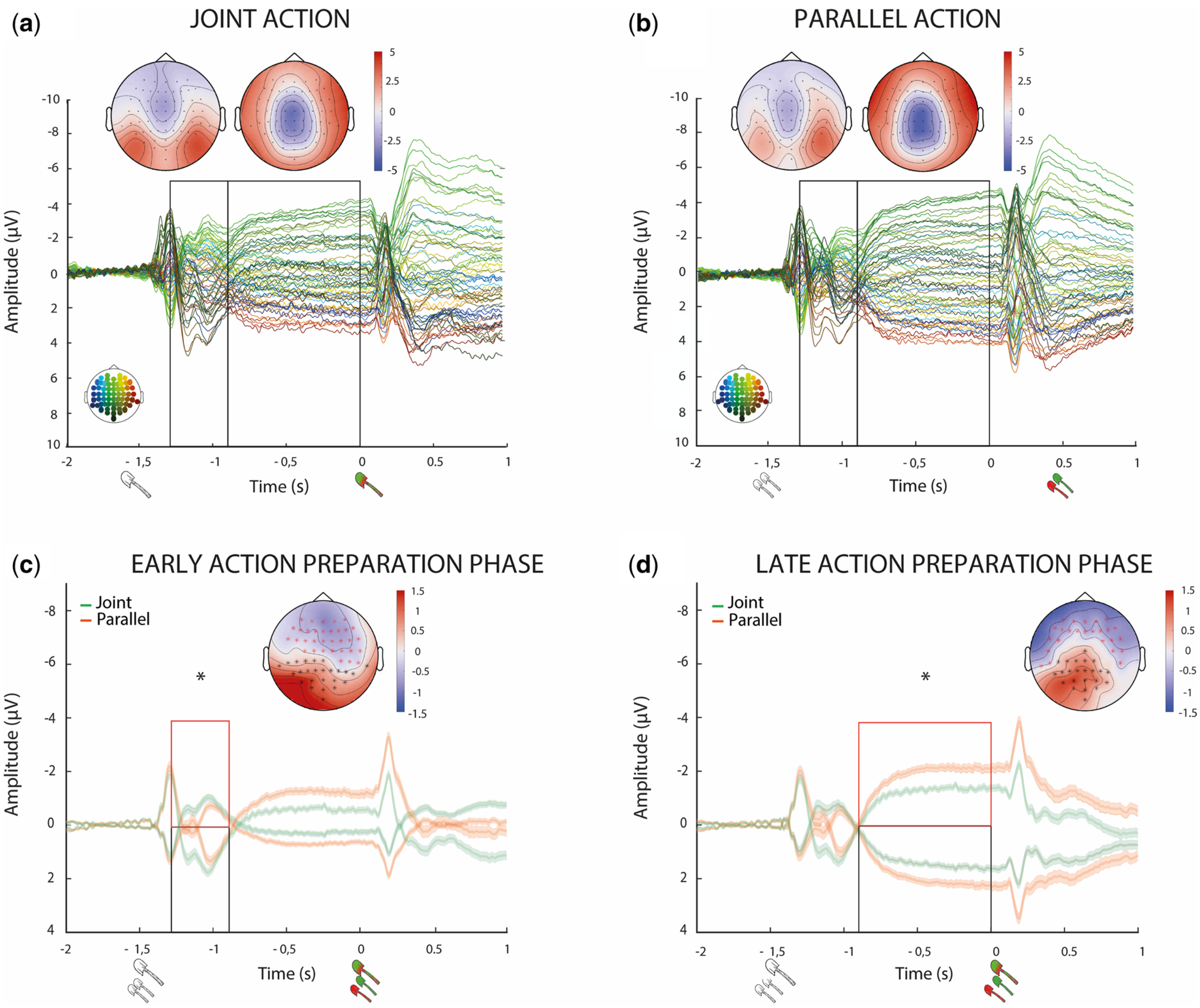

Figure 3. ERP Difference between JA and PA conditions (all Ps < .005). (a) and (b) show the butterfly plots of ERP measured in the JA and PA conditions, respectively. Each line represents the signal recorded from an electrode, as indicated by the colour code in the head at the bottom of the graph. Topographies above the butterfly plots represent the average topography in the time windows indicated by the black rectangles. (c) and (d) show the butterfly plot of the difference of ERPs (JA-PA). (c) represents the average signal from the electrodes of the positive and negative clusters for the early window; (d) represents the average signal of the two clusters in the late time window. White shovels represent the time of the cue signal, and coloured shovels represent the time of the go-signal. The above rectangles indicate the time windows of the significant negative clusters, while the below rectangles denote those of the significant positive clusters. Topographies above the rectangles indicate the spatial distribution of the clusters; red asterisks represent negative clusters, and black asterisks represent positive clusters. * P-value <. 05

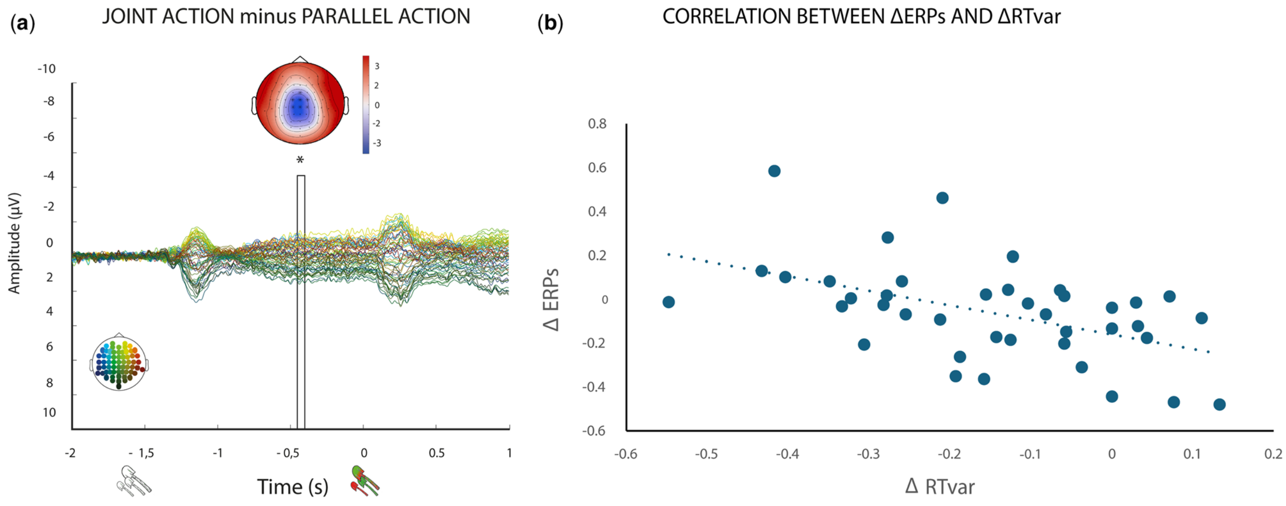

Figure 4. Correlation between ΔERPs and ΔRTvar. A significant difference was found in the cluster-based correlation analyses (*P* = .036). (a) Correlation between ΔERPs and ΔRTvar. A significant difference was found in the cluster-based correlation analyses (*P* = .036). (a) shows the butterfly plot of the difference of ERPs (ΔERPs) over time. The black rectangle indicates the time windows of the significant cluster. The topographic plot shows the electrodes included in the significant cluster (highlighted as black dots), superimposed on the average topography of the ERPs in JA and PA within the cluster time window. (b) Graphs show the correlation between ΔERPs in the cluster and the ΔRTvar. For display purposes, we calculated the cluster's mean value for each participant and plotted the correlation between these values and ΔRTvar. * P-value < .05

differences in RT and reaction time variability (RTvar) and compared ERPs simultaneously recorded from pairs of participants while they prepared to play a video game in which they had to transport a shovel *jointly* or in *parallel*.

We found that the success rate did not differ across conditions, indicating that the tasks were matched in terms of overall execution complexity. Participants were generally faster in the Joint than in Parallel Action condition. This reaction time difference suggests that, despite comparable task difficulty, action planning and initiation processes may differ across conditions. Participants adjusted their RTvars to match their partner's response pattern in both the joint and parallel conditions, with reduced overall variability observed in the Joint condition. The findings indicate that participants monitored and adjusted to their partner's action onset timing across both conditions, with mutual adjustment generally smoother when they acted jointly. Despite the instructions, it cannot be ruled out that competition occurred during parallel actions, which could have influenced the distinction between the conditions. However, this seems unlikely, as participants were slower to initiate parallel actions than joint ones.

ERP analysis revealed an intriguing swap in differences in ERP amplitudes between joint and parallel action preparation. Indeed, we found two distinct time windows with reversed patterns. A first, early time window (approximately from −1.250 to −880 ms) revealed a higher ERP amplitude in the JAt han in the PA condition, characterized by enhanced fronto-central negativity and occipito-parietal positivity. In contrast, the second, late time window (from −880 ms to 0) showed a smaller ERP amplitude in the Joint condition than in the Parallel condition, with reduced central-parietal negativity and fronto-lateral positivity.

These results showed the typical ERP components reported in CNV paradigms, including evoked responses to the stimuli and the CNV in the interval between them (Walter et al. 1964). After its discovery, CNV was refined in components: an early orienting wave (O-wave), occurring around 450–650 ms after the cue and larger at fronto-central sites, and a later expectancy wave (E-wave), larger at centro-parietal sites (Loveless and Sanford 1974). The first component is linked to cognitive processing and the properties of the first stimulus, and the second component is associated with expectancy and motor preparation (Weerts and Lang 1973, Rohrbaugh and Gaillard 1983). Although these two components have been fully distinguished when the interval between stimuli is longer than in our study, they are still observable in our data, suggesting that both the early orienting response and the later expectancy-related activity contributed to the CNV, even within the shorter interstimulus interval.

The swap we found corresponds well to the functional distinction of the O-wave and the E-wave components of the CNV. The first difference occurred in the time window of the O-wave and consisted of a higher amplitude for the JA than the PA condition. The second difference, in which the amplitude is higher for the PA than the JA condition, was in the time range of the E-wave. Therefore, the early effect likely relies more on the O-wave, while the later effect relies more on the E-wave.

It is worth noting that the topography of the effect in the early time window appears distinct from that of the later effect, and both differ from the topographies observed in each individual condition. This suggests that the early and late effects are generated by distinct cortical sources, supporting the interpretation that they reflect two separate neural processes. Furthermore, their cortical generators do not seem to fully overlap with those generating the main ERP components in the JA and PA conditions separately.

Given that the CNV results from widespread cortical activity, the differences between conditions may reflect changes in a subset of the cortical generators underlying the CNV. Alternatively, JA and PA might differ in the recruitment of additional neural sources that are not involved in CNV generation. Since the modulation is distributed across the scalp, it likely reflects changes in the activity of multiple sources—either within the original CNV network or involving newly recruited regions—including both frontal and posterior areas. Future studies are needed to individuate the spatial distribution of these effects in the cortex, possibly employing techniques with higher spatial resolution.

A characterization of the distinctive functions associated with the O-wave of the CNV is lacking. Nevertheless, there is evidence that it may primarily reflect cognitive processes providing a general preparedness to respond, such as stimulus processing, orientation, and anticipation in response to warning signal (Brunia and van

Boxtel 2001, Gómez et al. 2019). The O-wave is modulated by a broad spectrum of factors (Rohrbaugh and Gaillard 1983), such as stimulus features, cue saliency, and reward. Interestingly, specific motor preparation processes have been shown to already occur at the time of the O-wave (Bender et al. 2004). Therefore, it may be possible that this early response represents the integration of several task-related aspects, linking the processing of the cue with the representation of the goal. This could explain why the early response is higher in the JA condition, when participants had to represent a collective goal, than in the PA condition, where collective goal representation was absent. The fact that the stimuli presented in both conditions were virtually identical corroborated this explanation.

The reduction of the E-wave in the JA compared to the PA condition likely reflects motor preparation changes rather than temporal expectation. Indeed, the late CNV component related to temporal expectation is reduced when there is more temporal uncertainty on the go stimulus (Trillenberg et al. 2000, Praamstra et al. 2006, Mento et al. 2013, Breska and Deouell 2014, Duma et al. 2020). However, the go-signal did not differ in temporal uncertainty across the conditions. Furthermore, the CNV was reduced in the JA condition, which was characterized by a lower temporal response variability. This suggests that our results are unlikely to be explained mainly by temporal expectancy. Instead, a more likely explanation is that the reduction of late CNV in the JA condition is related to the modulation of motor preparation processes.

This explanation is also supported by the significant correlation between CNV amplitude changes and the variability in partner movement onset. Specifically, ERP differences between JA and PA conditions correlated significantly with differences in the partner's RTvar (but not with the agent's RTvar) during late action preparation. No correlations were found with RT per se. This seems to suggest that successful coordination with respect to the (collective) goal requires computing the variability of movement onset over time more than movement onset itself.

The less variable the movements are, the more predictable they are (Vesper et al. 2013, Sabu et al. 2020, also, Keller et al. 2007). The higher predictability of partner movements might, therefore, reduce demands on participants' motor planning in the JA compared to the PA condition, as the number of alternative movements that may have to be executed while coordinating with the confederate is limited, and movement parameters tend to be fixed across task repetitions. This is also in line with studies on CNV with ambiguous pre-cues (Jentzsch et al. 2004) and on readiness potential during action selection (Praamstra et al. 1995, Touge et al. 1995, Dirnberger et al. 1998), which all exhibited a reduction of the potential when movement variability was limited.

If our explanation is correct, the dynamic swap between early and late CNV components reveals fundamentally distinct processes between joint and parallel action preparation. The cognitive demands of representing collective goals may initially enhance neural activity associated with the early stages of action preparation, but these costs are offset later by enhanced mutual predictability, which facilitates action preparation. Participants considered partners' actions when acting in parallel, which enabled successful coordination. However, joint action involves more than considering others' actions (Bratman 2014, Ludwig 2016). Agents plan their own and others' actions collectively towards a shared goal. When these representations sufficiently match, as happened with participant dyads, action initiation is facilitated, increasing the likelihood of achieving the collective goal (Butterfill and Sinigaglia 2023).

Our findings appear to conflict with previous studies (Kourtis et al. 2014, 2019), which reported a greater late CNV amplitude when agents act together compared to when they act alone, attributing this to the representation of the other agent's actions. However, the conflict is more apparent than real. Indeed, performing a task with someone else is usually more complex than performing the same task alone, and evidence shows that late CNV increases for more complex tasks (Cui et al. 2000, Kranczioch et al. 2010). Our comparison of complexity-matched joint and parallel tasks revealed reduced late CNV amplitudes in the JA condition, correlating with increased predictability of the partner when shared goals were involved. Participants needed to consider their partners' movements in both tasks, yet distinctive late CNV patterns emerged. This suggests late CNV variations reflect others' action predictability rather than merely representing their actions (which occurs in both conditions). This interpretation also reconciles the increase in CNV when comparing solo action with joint action, as actions are more predictable when acting alone than when acting with others.

Finally, our results are consistent with recent studies that demonstrate planning and performing complementary actions create more significant interference when acting in parallel than when acting jointly. Formica and Brass (2024) found that drawing incongruent shapes (e.g. circle and diamond) disrupted participants' trajectories more in the PA than in the JA condition (see also Sartori and Betti 2015, Clarke et al. 2019). Interestingly, their EEG analysis showed that the incongruent movements were more discriminable in the PA than in the JA condition. As the authors suggest, this may result from forming an intertwined representation when acting jointly but not in parallel. Our results extend this suggestion, revealing that sharing a collective goal representation enhances action predictability by reducing interindividual variability at both behavioural and electrophysiological levels. Moreover, these findings may have important clinical implications, particularly for psychiatric conditions characterized by social interaction deficits (Schilbach 2016), such as schizophrenia, where CNV has emerged as a promising neurophysiological marker (Akgül et al. 2024).

Although further evidence is needed, our study provides a clear insight into the behavioural and neurophysiological processes that distinguish joint from parallel actions. Acting jointly entails a dynamic trade-off: the initial cognitive investment in representing collective goals yields benefits during late-stage action preparation through enhanced mutual predictability. Future research will benefit from examining how differences in action complexity, participant expectations, and agent variability may impact this dynamic trade-off influencing action preparation in both joint and parallel actions.

Author contributions

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Data availability

Row data are available at this link https://zenodo.org/records/16793625.

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