Disentangling the effects – Methodological critique of a hyperscanning protocol aiming at replicating the Joint Processing Effects

Antoine Bou Khalil, M.S.

Integrated Program in Neuroscience

McGill University, Montreal

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Contents

Abstract

Designing experiments to answer fundamental problems is a major methodological challenge. Over the last decade, a series of experiments investigated the human brains' ability to create phenomenological representations similar between individuals. They suggested an audacious answer to the so-called *Problem of the similarity of percepts*: that our brains might be physically attuned to the neural activity, and consequently to the percepts, of others. Using electroencephalography (EEG) to analyze event-related potentials (ERPs) evoked by visual stimuli presented simultaneously and privately to pairs of participants, they compared two conditions: in one, both participants were shown the same picture, whereas in the other, the pictures differed. They showed that the brain response of one participant differed depending on whether their stimulus matched their partner's, although the participants were ignorant of the manipulation. The present study aimed at replicating these Joint Processing Effects (JPEs) using an "optimal" version of this protocol, proposed by a previous study. We also introduced control trials where only one participant would see a picture to better characterize the effect. In a first part, we present our results using the "optimal protocol." Unfortunately, we observed no JPEs, but a parasite effect seemingly caused by the unbalanced block design recommended in the optimal protocol. Therefore, in a second part, we present a retrospective analysis of data from a previous, larger-scale study that used an allegedly balanced block design. We found the same parasite effect of the order, this time mixed up with JPEs. After investigating the possibility of experimenter bias in a subset of the old study's recordings, we were able to correct the parasite effect of the order and to properly isolate JPEs. This study highlights different methodological biases and proposes a revised "optimal protocol" aiming at avoiding them. It also provides a critical review of the interpretation of the Joint Processing Effects, of the conditions necessary to observe and study them, and of the implications and challenges of a potential brain-to-brain interaction at a distance.

Résumé

Concevoir des expériences pour répondre à des questions fondamentales est un défi méthodologique majeur. Depuis dix ans, une série d'expériences étudie la capacité du cerveau humain à créer des représentations phénoménologiques similaires d'un individu à l'autre. Elles proposent une réponse audacieuse au *Problème de la similarité des percepts* : notre cerveau pourrait être physiquement sensible à l'activité neuronale d'autrui. Utilisant l'électroencéphalographie (EEG) pour analyser les potentiels évoqués (ERPs) par des stimuli visuels présentés simultanément et en privé à deux partenaires, deux conditions ont été comparées : une où les deux participants voient la même image, et une où les deux images diffèrent, sans que les participants ne le sachent. Il a été observé que la réponse cérébrale d'un participant varie selon que son stimulus diffère ou non de celui de son partenaire. La présente étude vise à reproduire ces Effets de Traitement Conjoint (JPE) avec une version « optimale » de ce protocole, proposée par une étude antérieure. Nous avons aussi ajouté des essais contrôle où un seul participant voit une image afin de mieux caractériser l'effet. Dans une première partie, nous présentons nos résultats en utilisant le « protocole optimal ». Nous n'avons pas observé de JPE, mais un effet parasite lié à l'ordre de présentation des conditions, pourtant recommandé par le protocole optimal. Ainsi nous présentons dans une deuxième partie une analyse rétrospective de données d'une étude antérieure qui incorporait différents ordres de présentations. Nous avons constaté le même effet parasite lié à l'ordre des conditions, mélangé à des JPE. Après avoir étudié la possibilité d'un biais de l'expérimentateur dans un sous-ensemble des enregistrements, nous avons pu corriger l'effet parasite de l'ordre et isoler les JPE. Cette étude met donc en évidence différents biais méthodologiques et propose un « protocole optimal » révisé, et présente une approche critique des JPEs, de leur interprétation, des conditions nécessaires pour les observer, ainsi que des implications et des défis que présente une potentielle interaction entre cerveaux à distance.

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Introduction

Neuroscience of conscious perceptions

On the 26 of June 2023, the renowned neuroscientist Christof Koch lost a decade-long bet to the philosopher David Chalmers. The reason for his defeat: twenty-five years after the bet was made, no theory could '*clearly'* explain how our brain achieves consciousness. The question of consciousness has been an enduring one in the fields of neuroscience and philosophy since the first investigations of the human brain. In 1995, Chalmers suggested a division of this question into an "easy problem" and a "hard problem". The easy problem focuses on bringing functional descriptions of conscious perceptions. A major aspect of it is the identification of neural correlates of consciousness (NCCs), defined by Crick and Koch (1990) as '*the minimal neural mechanisms that are together necessary and sufficient for experiencing any conscious percept'*. Using different methods, inferences are made based on the observation of neural structures and activities that correlate with reported conscious experiences (see Dehaene & Changeux, 2011 for a review).

Particularly, the use of electroencephalography (EEG) and the analysis of event-related potentials (ERPs) can provide cues to the "when" and the "what" thanks to an acute temporal resolution. The EEG signals represent voltage variations over time detected at the surface of the scalp, which were shown to be caused by neural activity in brain, thus revealing the neural correlates of specific sensory, motor or cognitive events (Hillyard & Picton, 1987). Many ERPs have been identified and correlated with specific stimuli, context, and cognitive events. For instance, the N170, a negative component peaking around 170 ms after a stimulus' onset, was specifically observed in participants being shown pictures of faces (Bentin et al., 1996) yet its observation is unrelated to the specificity of a given face (Schweinberger et al., 2016) and as such is interpreted as a very early indicator of perception. The N170 is considered a

NCC as its amplitude was shown to be greater in case of conscious face perception (Harris et al., 2011, Navajas et al., 2013).

Diverse ERPs have been identified that correlate with the report of conscious perceptions. For instance, the late posterior positivity's (LPP) amplitude was correlated with the report of subjective perception (Ye et al., 2024, Sun et al., 2024) and associated with the activation of brain regions generally implied in conscious processing. Another widely studied ERP is the N400, a negative component peaking between 300 and 500ms after stimulus' onset, which is largely accepted as an indicator of the processing of semantic information (Kutas et al., 2006). This component is sensitive to a diversified set of semantic relations, may they be categorical, functional or linguistic (see resp. Bach et al., 2009, Heinze et al., 1998, Kutas and Iragui, 1998) to cite those only. Its amplitude has also been correlated to the cognitive load involved in a task (Chwilla et al., 1995, Kutas and Federmeier, 2000, Kuipers and Thierry, 2011). However, the versatility of this component has led to a still-ongoing debate to determine wether the N400 characterize processes of inhibition (Debruille, 1998 & 2007, Shang and Debruille, 2013, Sinha et al., 2023) or activation (Ferretti et al. 2007, Liu et al., 2010, Metusalem et al. 2012). Such a specific controversy clearly illustrates how un-easy the "easy problem" can become when one wants to precisely characterize a CNN.

Another aspect of the easy problem is the characterization of what we call "consciousness" as a global neural phenomenon. Various conscious states have been correlated with global patterns of neural activity, leading some authors to argue that consciousness relies on the organizational properties of the neural networks rather than on the intrinsic properties of specific neurons (Dehaene & Naccache, 2001). The "global neuronal workspace" theory postulates that a neural process is made conscious when a large-scale neural population is associatively activated following top-down attentional processes (Dehaene & Naccache, 2000). Other theories suggest that the experience of consciousness corresponds to the activation of a dynamic core constituted of an interactive network of neural groups (Tononi and Edelman, 1998).

The hard problem focuses on the "how" and the "why": how do physical phenomena (such as a photon with a certain wavelength) causing electro-biochemical activity in our brain generate a percept (the phenomenological red) in our mind? The term "percept" designates here the subjective experience created by the brain in response to a stimulus. The percepts form the '*3D movie*' (Chalmers, 2014) that constitutes our impression of our environment, including ourselves, our thoughts, and our sensations, i.e. our perceptual world. In Chalmers' conception, the hard problem differs from the easy ones in that a complete and extensive physical and functional explanation of the brain's activity will not answer the question: "why is the performance of these functions accompanied by experience?" (Chalmers 1995). Indeed, many thought experiments aim at demonstrating that there is something inherently non-physical to the experience of consciousness, such as the famous knowledge argument (Jackson, 1982): the demonstration claims that Mary, a super-scientist, all-knowing of the physical properties of the universe but raised in a black-and-white box, would still "learn" something once out of the box. However, this thought experiment has received many responses and counterarguments, and Jackson himself now considers himself a physicalist.

What is of interest for us in these responses is what they say of the scientific approaches that arose in reaction to the hard problem. Some scientists, such as Daniel Denett, entirely refute the "hard problem" and argue that solving all the "easy problems" would lead us to a level of understanding sufficient to explain the subjective experience of consciousness. Other thinkers recognize the specific nature of the hard problem while still considering it solvable by the scientific method. This is the case of Francisco Varela who developed the field of Neurophenomenology as a pragmatical way to explore phenomenological problems by incorporating notions of phenomenology and the first-person approach into the third-person vision of cognitive sciences (Varela, 1996). It notably incorporates an embodied approach of self-reports freed from one’s theories and expectations about perception (Thompson et Varela, 2001, and see Gallagher, 2009, for a review). The neurophenomenological approach also values the subjective variability that is generally obliterated by averages and noise canceling in studies (Lutz et al., 2002). Neurologically, the approach is focused on large-scale analyses of brain activity and the study of emergent patterns rather than isolated effects (Rodriguez et al., 1999).

Even though the experiment presented in this study does not adopt a neurophenomenological approach, it was designed to address a problem parallel to the “easy” and “hard” problem, the problem of the similarity of percepts.

The problem of similarity of percepts

The subjective nature of the percepts raises questions regarding their similarity from one individual to the next: since our percepts are inherently personal, how can we know whether they are identical to those of the people around us? Even though our understanding of the processes that generate conscious perceptions has expanded exponentially since Koch and Chalmers’ bet, the “hard problem” of consciousness remains far from being solved. As long as it remains, we are ignorant of the detailed pathways that lead from the physical world to a person’s perceptual world. Consequently, we have no certainty that different individuals presented with the same physical world will build the same percepts in the intimacy of their minds. However, if the percepts were too different between individuals, it would be difficult for them to communicate about their environment, let alone cooperate like humans do. In fact, in our everyday life, we assume that our perceptual world is close enough to that of others.

Our ability to communicate does not actually prove that our percepts are equal, but at least that we apply the same terminology to similar levels of difference. For instance, most people seem to perceive a similar level of difference between the colors called “blue” and “red”, so that I can talk about a blue and a red object with another person and we’ll agree on using two different words for the objects. It might be, however, that their percept of blue corresponds to my percept of red and reversely, but we would never be able to know it as only the difference matters. This thought experiment is known as the “inverted spectrum world” and has been at the core of many philosophical debates (see Byrne, 2018 for a review).

The problem of similarity of percepts addresses the questions of whether and how different people’s brains build similar percepts. In this part, we will explore what is known or assumed about the similarity of percepts between individuals, as well as different mechanisms by which humans can build similar percepts.

To start addressing this question, it is important to note that a percept is not a product of an isolated physical stimulus. To quote Crick’s words (1996): “What you see is not what is really there; it is what your brain believes is there”. This formulation underlines the importance of the inferences computed by our brains. A physical stimulus is never treated by itself, but it is considered in the light of all the other information accessible to our brain. Among the elements that can influence the formation of a percept are the people around us.

To a certain extent, the similarities between our brains provide a physiological answer to the similarity of percepts, and investigations of the “easy problem” of consciousness have largely demonstrated that conscious perceptions correlate with specific neural activities that are identical between individuals. However, sometimes, a similar stimulus leads to different percepts. From one population to the next, we can observe that brains are attuned to different level of discrimination between certain perceptions. For instance, most native Japanese speakers hardly distinguish the “r” and “l” sounds in speech (Goto, 1971), a perceptual difference that is observable at the neural level (Koyama et al., 2003) but can be overcome through early training (Guion et al., 2000). This shows us that the mechanisms implied in the construction of percepts have a certain plasticity, and that the ability to differentiate specific stimuli can sometimes be acquired through cooperation with the people around us – here through learning.

That we can refine our percepts through communication with others is no surprise. The influence of the surroundings on learning has been extensively explored in the literature. Infants first learn to put words on their perceptions through observation of the adults around them (Medina et al., 2011, Trueswell et al., 2014, Srinivasan, 2017). Even adults adapt their vocabulary depending on the lexical innovations happening in society (Asif et al., 2021). It has even been shown that individuals adapt what they pretend to perceive to conform to a group (Ash, 1951). Yet these observations only go one way: putting a common word on something we perceive. The debate here goes beyond this and asks whether interactions with other individuals can influence the perception itself, therefore with changes at the neural level.

Exploring two-brains interactions

In the last decade, hyperscanning, a method consisting in the simultaneous recording of two or more participants' neural activities (Montague et al., 2002), has become more and more prevalent to explore coinciding brain responses during human interactions. Experiments using this technique have revealed brain coupling mechanisms between participants involved in social interactions with each other (Dumas et al, 2010, see Dumas, Lachat, Martinerie, Nadel, & George, 2011, Konvalinka & Roepstorff, 2012 for reviews). Those studies have correlated known behavioral patterns of synchronisation (Schmidt et al., 1998; Richardson et al., 2007; Konvalinka et al., 2010) with neural events, leading to a better understanding of the underlying neural mechanisms. Of course, the interpretation of these observations remains delicate and subject to debate (Zimmermann., Schultz-Nielsen, Dumas & Konvalinka, 2023). It might seem that brain coupling only reflects the identity in the two participants' actions, however, studies have shown that *‘[brain coupling] cannot be reduced to the activities of each brain taken separately and is not only caused by the similarity of action and perception of the two players’* (Dumas, 2011). It is interesting to note the innate nature of brain coupling, as it is observed as early as in the newborn brain (Bembich et al., 2024). Altogether, such discoveries demonstrate how interacting with others evokes changes at the neural level – and so, how the people around us could influence our percepts directly at the neural level.

In the following parts of this introduction, we will present a series of studies that investigated this idea one step further by exploring whether the percepts of others could directly influence the creation of our percepts: their surprising observations indeed suggest a potential brain-to-brain interaction at a distance. If it exists, such a mechanism could participate in the formation of similar percepts across individuals. The specificity of those studies was that participants were not involved in social interaction during the experiment, unlike in the hyperscanning experiments which observed brain-to-brain coupling. While brain coupling is interpreted as the result of behavioral feedback, the following series of experiments presents a possibility of neural interaction between two isolated participants separately processing visual stimuli.

They rooted this audacious hypothesis in two physiological observations, namely our brains’ sensitivity to electromagnetic waves, and the electromagnetic fields produced by neural activity. The former is reflected in the numerous studies using Transcranial Magnetic Stimulation (TMS), a method that proved possible to impact neural activity with an external source of magnetic waves (Kerwin et al., 2018). TMS has notably been used to clinical ends, with a possible impact on motor impairing (Bohning et al., 1999, McDonnell and Stinear, 2017) or on some neuropsychiatric disorders such as schizophrenia (Cole et al., 2015). Apart from TMS, a team has found the brain to be sensitive to magnetic fields as small as the Earth’s (Wang et al., 2019). As for the magnetic field produced by the brain, its recording is at the core of Magnetoencephalography (MEG), certainly the leading method to study the dynamics of neural activity. Whether brains can exploit these phenomena – or any others – to initiate brain-to-brain interaction at a distance had yet to be demonstrated; and even though Bouten et al.'s study indeed found an electrophysiological effect at a distance, neither their nor any of the successive studies has yet revealed an explanatory mechanism. At the best, alternative hypotheses have been ruled out. It is not the purpose of the present study to explore the vector supporting the interaction; nevertheless, we will review in the discussion other mechanisms that have been proposed, and the reasons why the electromagnetic hypothesis is currently predominant despite the challenges it faces. Indeed, these questions pave the way of further research and will have to be answered at some point in the future.

This study focuses on replicating the surprising Joint Processing Effects observed in four successive studies supervised by Dr. Bruno Debruille over the last decade. We will now review these studies with a specific focus on the different experimental choices they made, and the evolution of the protocol that were proposed as the investigation advanced.

Study-specific reviews

Initial experiment by Bouten et al. (2014)

Bouten et al. (2014) suggested that a person's brain might be sensitive to someone else's brain activity – and thus production of percepts – at a distance. To test this hypothesis, they recruited pairs of participants and exposed them to visual stimuli, privately and simultaneously. From a participant's perspective, all the trials had a similar setting, whereas in reality the participant and their partner were shown identical pictures during half of the trials only; during the other half, the two participants were shown different pictures. Bouten et al. used EEG to investigate whether a participant's neural activity was influenced by the other participant's simultaneous processing of a stimulus.

They recruited pairs of socially close participants (relatives, close friends, significant others, etc…), as they suggested that social closeness would improve the hypothesized sensitivity. It seemed plausible that if a brain was sensitive to another brain's activity, we would be more sensitive to the people that we are used to having around us, in the same manner that a musician's ear is best attuned to its instrument. They recorded the ERPs evoked by pictures from the International Affective Picture System (IAPS - Lang et al., 1997). At each trial, two pictures were displayed on a screen, respectively on the right and the left of it. A cardboard divided the screen in the middle, also separating the participants so that each participant would only see one of the two pictures and couldn't see the picture presented to their partner. They manipulated the sameness of the two pictures (Same vs Different) and the announcement made to the participants regarding this sameness (either Concordant or Discordant). This resulted in four experimental conditions, two concordant ones (Different-Announced-Different = DAD, Same-Announced-Same = SAS) and two discordant ones (Different-Announced-Same = DAS, Same-Announced-Different = SAD). The experiment was divided into 4 blocks corresponding to the four conditions. The order of the four blocks was pseudo-randomly manipulated from one pair to the next, using a Latin square.

They computed the ERPs corresponding to the different conditions by averaging the stimuli-epoched EEGs from each of the four blocks. Then, they proceeded to within-subject comparisons by comparing the ERPs evoked by four conditions. All blocks were identical from a participant's point of view, so a difference in the ERPs would be an indicator that the participant might have been sensitive to what was shown to their partner.

Bouten and al. found the ERPs to be modulated by the two factors concordance of the announcement and sameness of the pictures, individually and in interaction. The ERPs were more positive in the discordant conditions (SAD, DAS) than in the concordant ones, despite the participants' ignorance regarding the sameness of the pictures and thus the veracity of the announcements -as verified in debriefing sessions. A significant difference was observed between the ERPs of the SAD and DAD conditions, but not between the SAS and DAS conditions (see **Figure 1**). The effects were mostly observed in the N400 and the late posterior positivity (LPP/P600) components. The effect was widespread over the scalp for the LPP and restricted to the sagittal subset of electrodes for the N400. It was observed for both participants sitting on the left and the right of the desk. However, only the participants sitting on the left showed the effect at frontal electrodes.

The authors interpreted these results as support to the hypothesis that the partner's processing of the visual stimulus impacted that of the participant. They called these effects "Joint Processing Effects" (JPEs).

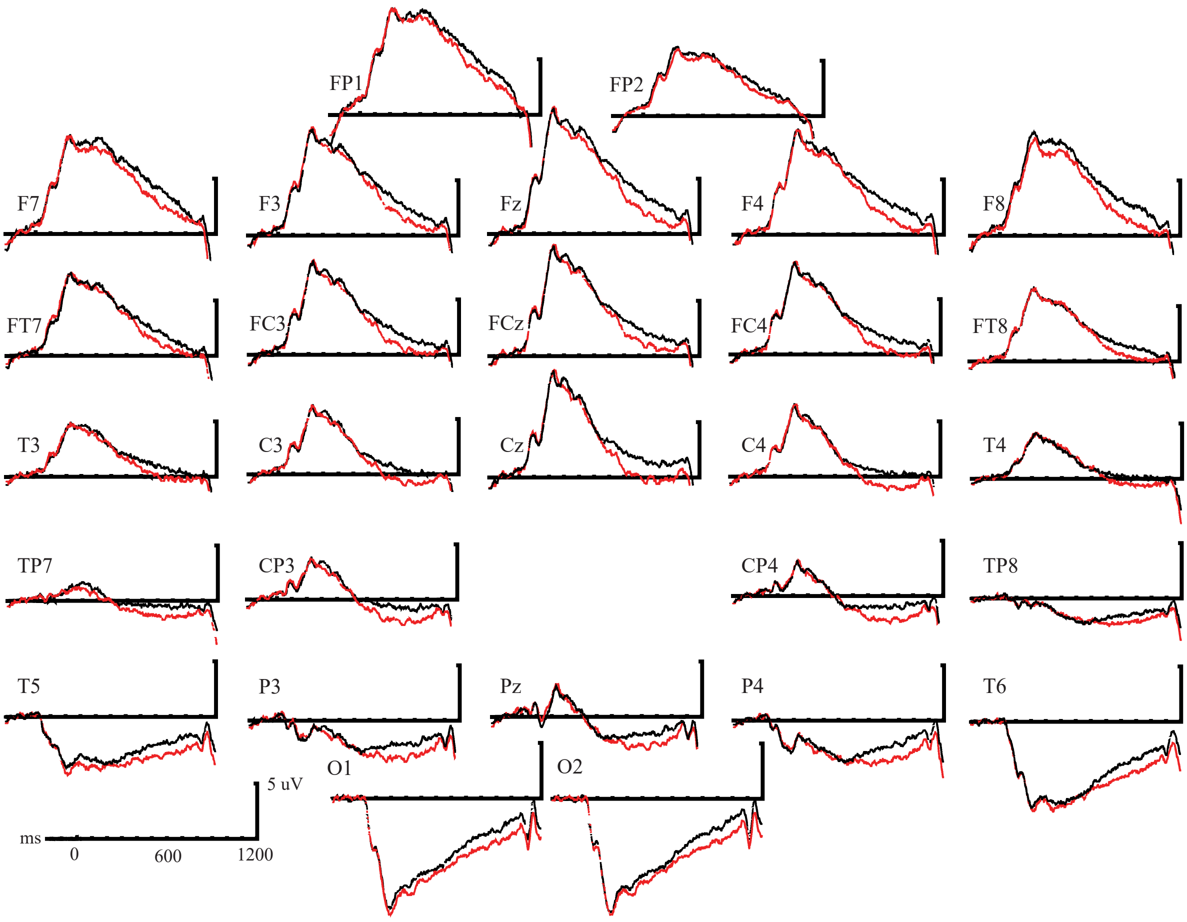

Figure 1 - Grand average ERPs from Bouten et al., (2014). N = 32. The red lines are the ERPs of the SAD block. The black lines are the ERPs of the DAD block.

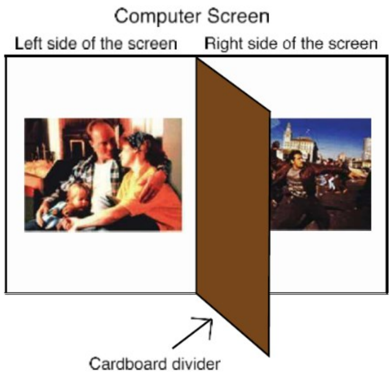

Figure 2 - Schematic representation of the simultaneous presentation of visual stimuli to the two participants, from Bouten et al. (2014).

Replication attempts and evolution of the protocol

Further studies reiterated the experiment whilst improving the design. A major concern of the first study was the weak separation medium between the two participants. The IAPS bank of pictures provides a wide range of images depicting diverse situations, some of which are very light-hearted – e.g. a happy family at home – whereas others are emotionally charged – pictures depicting violent scenes or even pictures of sexual nature. With only a cardboard separating the screen in two, participants could have noticed changes in the attitude or the posture of their partner, consciously or not. This could give the participants a cue as to whether their partner was seeing a picture of a similar emotional load as their own. In Haffar et al. (2018), a curtain was installed to divide the room in two and ensure visual isolation of the participants. They replicated the results of Bouten et al. (2014) in terms of direction: the ERPs evoked by the SAD trials showed more positive N400 and LPP components than the DAD trials (see **Figure 3 top**). No significant difference was observed between the ERPs evoked by the SAS and DAS trials. However, the intensity and localization of the JPEs varied slightly and the JPEs were not observed at occipital electrode sites in Haffar et al.'s results.

They also ran the experiment with pairs of strangers to test the influence of the closeness of the two participants. This time, almost no JPEs were observed, the slight difference of ERPs between the SAD and DAD conditions being much smaller than when closely related participants were tested (see **Figure 3 bottom**). It was determined that pairs of closely related participants should be recruited in further studies to evoke a stronger effect.

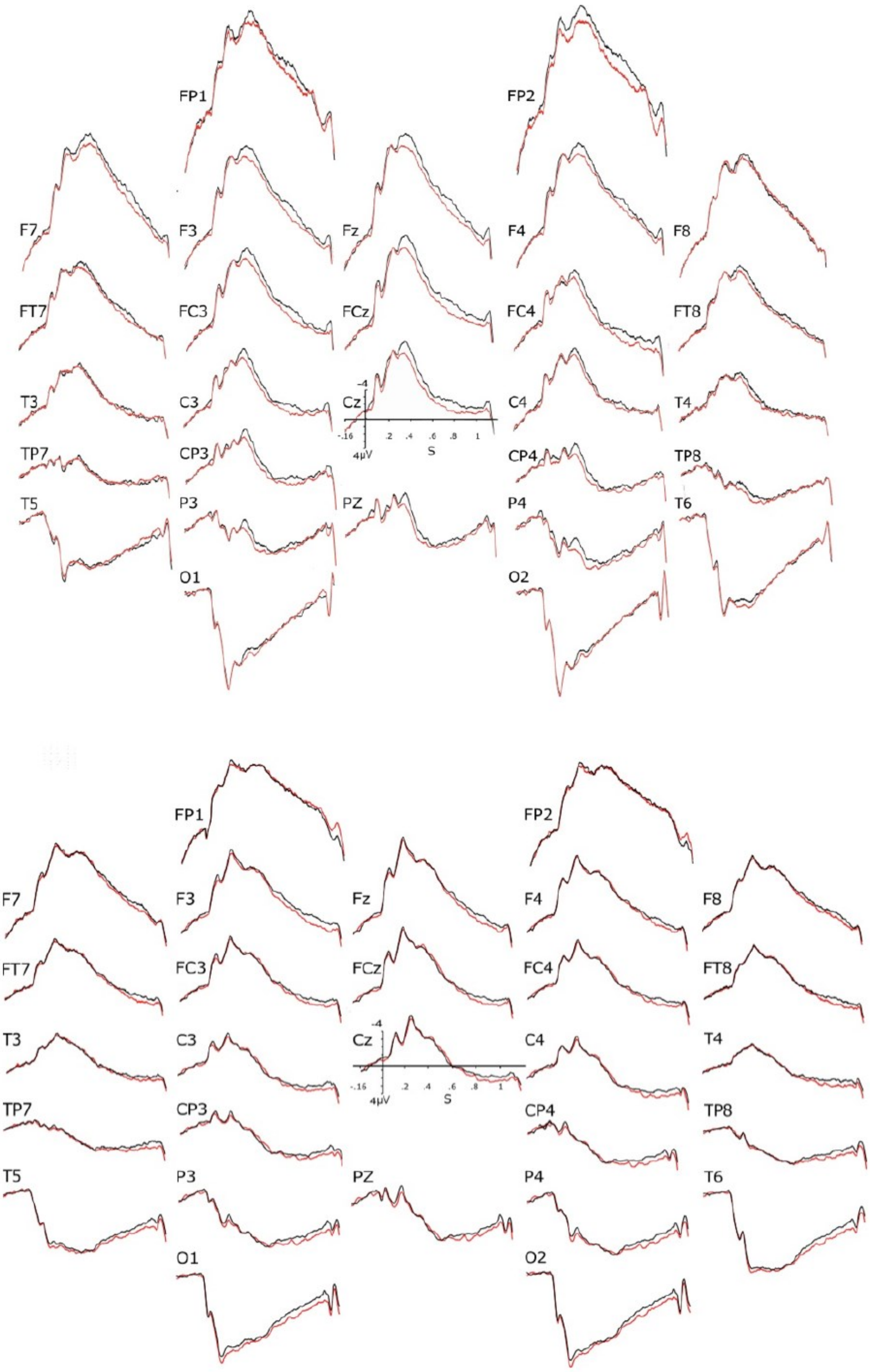

Figure 3 - Grand averaged ERPs from Haffar et al. (2014) for pairs of closely related partners (top) and pairs of strangers (bottom). Black = DAD, Red = SAD

Tardif et al. (2020) used a similar protocol but separated the participants in two adjacent rooms to ensure auditory separation. Indeed, gasps or changes in breathing could indicate to a participant that their partner was seeing a picture different than theirs. They recruited pairs of closely related participants to match Haffar et al.'s observations. For this study, they implemented a mixed design rather than a block one in order to avoid effects of fatigue or repetition (Humphrey, Kramer, & Stanny, 1994, Polich & Kok, 1994). Although a Latin square was used in Bouten et al. (2014) and Haffar et al. (2018), Tardif et al. were concerned that a time-on-task effect could develop during a block and impact the ERPs of the next. To avoid this, the different types of trials were randomly mixed throughout the experimental session. Also to limit fatigue, conditions were restricted to the two that showed a significant difference: DAD and SAD. Thus, the only announcement made to the participants was that the pictures would be different.

As the authors were concerned that the physical distance might impair social cognition, the participants were asked to try and feel in the presence of each other despite being physically separated. After the experiment, the participants were asked if they had felt in the presence of their partner for more than 50% of the experiment and separated into a "Felt together" and a "Felt alone" group in the analyses.

This time, grand average ERPs only showed a scarce effect on a restricted number of electrodes in the 350-650ms time-window only (see **Figure 4**). However, using the Monte Carlo Method revealed idiosyncratic effects in individual participants which, to this day, remain to be explained. It was hypothesized that the Joint Processing Effects would only occur under a particular cognitive state or strategy. Cognitive states can be broadly defined as "a recurring set of neural conditions that is stable for a behaviourally significant period of time" (Zagha & McCormick, 2014) and can be observed at different temporal scales. Generally, changes of cognitive states are related to behavioural changes such as reaction time or discrimination threshold variations (Yamashita et al., 2021, Wu et al., 2020). They are often physiologically identified at the network level, e.g. the different attentional states, that were shown to be identifiable in EEG data (List et al., 2017, Rogala et al., 2020) or the state of "alertness" that has become a main focus of studies on the impact of smartphone overuse on slowed stimulus treatment (Abdullah et al., 2016). It has even been observed that the current state of the brain can impact its reaction to direct neurostimulation (Bradley et al., 2022). However, attentional states can vary on a trial-by-trial basis, whereas the hypothesized cognitive state associated with JPEs would develop and remain on a longer temporality, similar to sleep states (Hasan et al., 2020, Simor et al., 2020). This cognitive state would be induced by exposition to stable conditions for a time long enough, which is not the case when a mixed design is used. Therefore, only block designs have been used since.

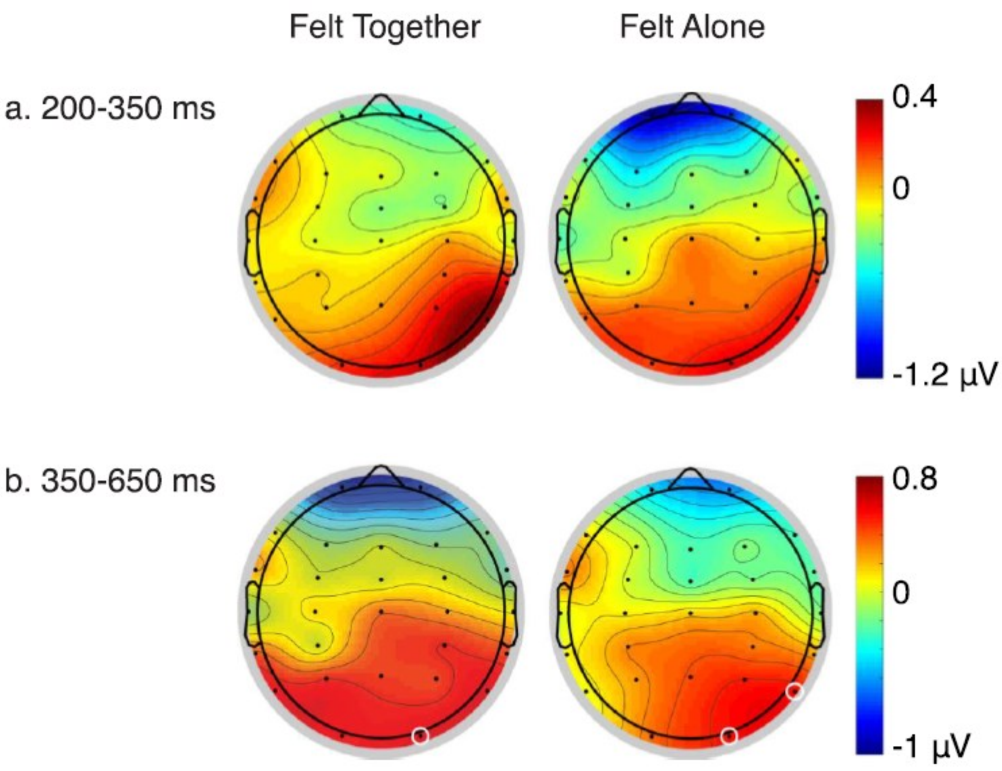

Figure 4 – From Tardif et al. (2019). Mean voltage subtractions (concordant minus non-concordant) in the (a) 200-350 ms and (b) 350-650 ms time-windows. A mixed design was used here. A ring indicates a statistically significant difference in mean voltages in those time-windows discovered when testing that electrode separately using a paired samples t-test in that group (p<0.05).

The most recent attempt at replicating the JPEs was made by Jeuland et al. (2022). They used Tardif et al.’s (2018) setting, this time with a block design. They recruited pairs of closely related partners and had them sit in two adjacent rooms. An experimental session consisted of two blocks of a hundred trials each, a Same-Announced-Different block and a Different-Announced-Different block. The order of the two blocks was randomised, resulting in participants having either the SAD block first or the DAD block first.

Jeuland et al. (2022) used the Multipurpose bank of European Descent faces (the MED bank, Debruille et al., 1999) as stimuli instead of the IAPS pictures. The MED bank is a series of neutral-looking faces. Faces elicit very characteristic components such as the N170. This results in less noisy ERPs after the averaging of epoched EEG signals. One can also expect a more localised effect on the scalp, as the range of emotions associated with the faces is narrower than that of the IAPS images, and effects of surprise are less likely.

They reiterated the Felt-together/Felt-alone separation after having asked the participants to try and feel in the presence of their partner. The participants were asked four times during the experiment if they had felt in the presence of their partner, and those who answered “Yes” three times or more formed the Felt-together group in the analyses.

Additional pairs of partners were recorded using the same protocol after the submission of Jeuland et al. (2022) to increase the pool of participants. Analyses on the complete dataset were conducted by Calmels et al. (2023) to assess whether the feeling of presence and the order of the blocks had an impact on the Joint Processing Effects. An impact of both factors and an interaction between the two was revealed by these analyses. First of all, significant Joint Processing Effects were exclusively observed in the FT group (see **Figure 5**). Secondly, within the FT group, it was observed that presenting the DAD block first and the SAD block second elicited a much stronger effect than in the reversed order (see **Figure 6**).

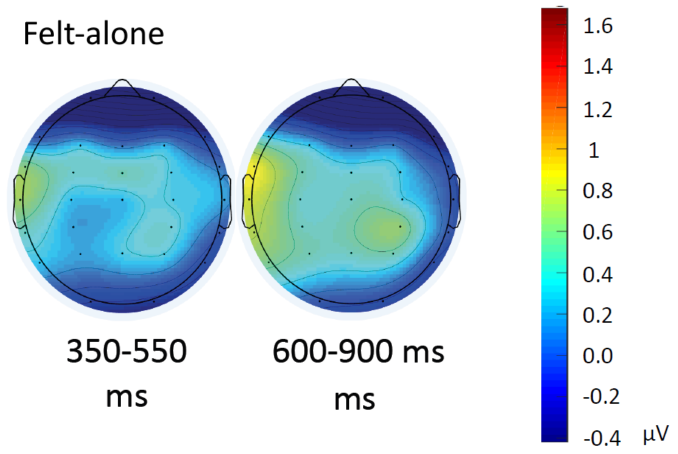

Figure 5 - From Calmels et al. (2023). Mean voltage subtractions (SAD minus DAD) separated by reported feeling of presence in the 200-350 ms and 350-650 ms time-windows. DAD-first group only. Stars represent a significative difference from 0 at paired samples t-test (: p<0.05, ** : p<0.01, *** : p<0.005).*

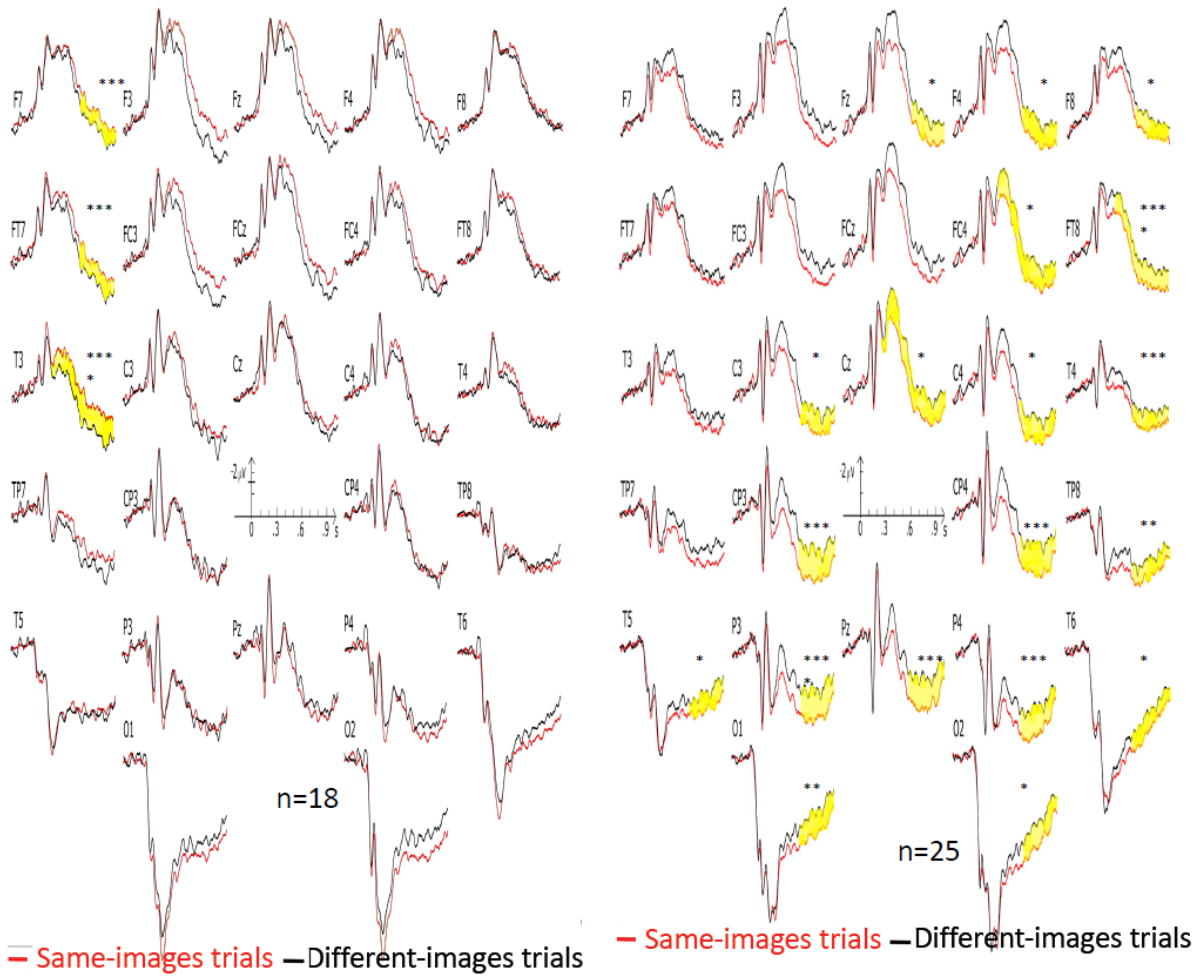

Figure 6 – From Calmels et al. (2023). Grand averaged ERPs separated by order of the blocks. Left: SAD-first group. Right: DAD-first group. Felt-together participants only. Yellow areas represent a significative difference between the two conditions at paired samples t-tests (: p<0.05, ** : p<0.01, *** : p<0.005).*

Finding an impact of the order echoed the failed attempt at using a mixed design by Tardif et al. (2019), which suggested that a global cognitive state had to be induced by a stable situation to observe JPEs. If JPEs occur in a certain cognitive state, the first block will determine the cognitive state in which the participant is. Results suggest that the state induced by an SAD block is more persistent than that induced by a DAD block. In the SAD-first condition, it persists for the whole experiment, and no difference is observed between the blocks. Finding an impact of the feeling of presence underlined the importance of maintaining this feeling even though the participants are physically separated.

The successive studies of the Joint Processing effects have led to the determination of an "optimal protocol," i.e. an ensemble of experimental conditions susceptible to eliciting the strongest JPEs. The study presented in this thesis aimed at replicating the JPEs using this optimal protocol while refining the characterization of these surprising effects.

Present study

Motivation and rationale

The following study first aimed at replicating the Joint Processing Effects. We applied an "optimal protocol" using the conditions determined after Calmels et al.'s (2023) analyses as the ones that elicited the most robust effects in the previous experiment. The five optimal conditions were:

1) Having pairs of closely related participants (close friends, relatives, romantic couple, etc.), as Haffar et al. (2018) showed that no significant JPEs were observed in pairs of strangers.

2) Using a block design with the different-pictures (DAD) block first. Tardif et al.'s (2019) attempt to use a mixed design found no JPEs in grand averaged ERPs. Even though they had revealed the existence of idiosyncratic effects, we have not chosen to explore this path here

and will focus on effects observed in grouped analysis. As for the order, Calmels et al.'s (2023) had found that JPEs were stronger with the DAD block first.

3) Announcing to the participants that they would see different pictures. It had appeared as soon as in Bouten et al.'s (2014) experiment that only the comparison of the SAD and DAD conditions showed significant differences. Limiting the experiment to those two conditions also limits fatigue effects.

4) The participants' only task is to try and memorize the faces. Since Bouten et al.'s first study, the participants have been instructed to try and memorize the pictures displayed on the screen. The first study also included a memory test, which has now been discarded. However, the instruction to memorize the pictures remained in the following studies. Memorizing is a simple, repetitive and passive task that does not require any parasite movement, whilst the expectation of a memory test encourages the participants to remain focused on the task.

5) Engaging participants to "feel in the presence of their partner", as it was observed by Calmels et al. (2023) that the effect was stronger in the participants who reported having felt in the presence of their partner.

Our second goal was to assess the robustness of these conditions, which have been determined through analyses of data gathered from different studies. Although supposed to be similar in methods, the studies described earlier were run at different moment by diverse experimenters, and each has brought its share of novelty to the protocol. It is essential to provide the literature with a robust and validated protocol so that other teams can attempt to replicate our findings. We kept the same setting that has been used since Tardif et al. (2019), so no modifications were brought on the material aspect. In the discussion part of this thesis, and in light of our own results using this "optimal protocol", we will present critical points of reflection regarding this protocol and suggest corrections to it where necessary.

Thirdly, this study aimed at refining the characterisation of the JPEs. We implemented control conditions where only one of the two participants saw a picture. This aimed at defining a baseline-ERP for our visual stimuli, to determine whether JPEs were a deviation from this baseline, and if so in which direction. However, the addition of those control trials presented an experimental dilemma. If we had included a "control block" with all the control trials, it would have been necessary to also test the impact of this new block depending on when it occurred relatively to the two other blocks, i.e. before the DAD block, between the DAD and SAD blocks, or after the SAD block. This would force us to recruit three times as many participants. The remaining option was to mix the control trials within the DAD and SAD blocks. This was taking the risk of recreating a mixed design. However, the main conditions (SAD or DAD trials) remained predominant within the blocks compared to the controls, so we supposed that the brain would still adopt the corresponding cognitive state. Indeed, previous studies have shown that JPEs can be observed at various levels of difference between the SAD and DAD blocks: although different, the two pictures from the DAD block in Jeuland et al. (2022) are still two pictures of faces, therefore much similar to each other than two random IAPS pictures, and yet JPEs were successfully observed in those conditions.

Finally, we collected behavioural data through validated questionnaires and a debriefing session. Prior experiments have shown an influence of the social context on JPEs, so we expected the observation of JPE and their intensity to correlate with different scores such as the two participants' closeness, their ASQ score, etc. Whilst not all those data will be exploited here, this constitutes a strong basis for potential future retrospective analysis. Taking the participants' subjective experience into account might also help in understanding the versatility of prior observations. Notably, we wanted to identify the cognitive strategies adopted by the participants and whether they were correlated with specific ERP patterns.

Material and Methods

Participants

20 pairs of closely related participants were recruited (N=40; 5 M) for this study through online advertisements. Our inclusion criteria were: being right-handed, between 18 and 30 years of age (M=22, SD=3.1), normal or corrected-to-normal vision, fluent in either English or French, having known their partner for at least 3 years and having a degree or being in the process of completing a university degree. The exclusion criteria were: drug or alcohol abuse (more than twelve beverages a week), family or personal history of psychiatric disorders. Both partners of a pair had to fill in an online self-report eligibility questionnaire and would only be offered to participate in the study if both met all the criteria.

Consent

All participants read and signed the informed consent form prior to the experiment. Both the consent form and the study itself were accepted by the Douglas Ethics Review Board of the Douglas Mental Health University Institute. This board follows the principles expressed in the Declaration of Helsinki. Data were anonymized using codes, which did not impact the study and data collection.

Stimuli

We used pictures from the Multipurpose bank of European Descent faces (the MED bank, Debruille et al., 1999) as visual stimuli. Those pictures are a curated collection of faces with standardized view, size, background, color, contrast, and luminance. The participants posing as models had been asked to keep a "natural" expression. Thus, the MED bank constitutes a homogeneous yet naturally diverse collection of portraits.

The use of faces instead of IAPS images, as in the earliest JPE experiments, aimed at producing more similar and easily characterizable ERPs. We chose the MED bank rather than more recent AI-generated pictures because we found the latter to be too identical, which would make the memorizing task harder and potentially impair the participants' focus.

A total of 560 pictures were selected within the database. We rejected pictures of models whose face was tilted or abnormally high or low in the frame, to limit eye movements of the participants. The pictures were divided into three folders of 140 pictures and two folders of 70 pictures to be used for the main and control conditions respectively. The assignment of the folders to the conditions was randomized from one pair to the next.

Each stimulus was presented for 1000 ms. The inter-stimulus-interval length was randomized between 200 and 1200 ms. To ensure synchronicity of the stimulus presentation, the two pictures were displayed together on one screen and sent simultaneously to both participant's monitors. Each participant had one half of their respective screen hidden so that they could only see one picture. One participant saw the picture on the right of the screen, and the other participant saw the picture on the left.

Trials

At each trial, a picture is shown on a white background and followed by a black fixation cross. Trials where both participants see a picture correspond to the main conditions. Trials where each participant sees a different picture correspond to the Different-Announced-Different (DAD) condition. Trials where both participants see the same picture correspond to the Same-Announced-Different (SAD) condition. The full experiment counted 140 DAD and 140 SAD trials strictly separated in two different blocks.

Other types of trials correspond to our control conditions. First, we added trials where only one participant saw a picture, while the other participant would be shown a fixation cross for the duration of the stimuli. These trials were labeled Image No Image (INI) for the participant who saw the picture and No Image Image (NII) for the participant who saw the fixation cross. The experiment counted 70 INI and 70 NII trials per participant.

We also added a No Image No Image condition (NINI) where both participants saw the fixation cross. The experiment counted 70 such trials. The control conditions were evenly distributed within the two blocks. Within a block, the controls were pseudo-randomly distributed to ensure global homogeneity whilst avoiding redundant patterns. By the end of the experiment, each participant had seen 350 faces in total.

Procedure and instructions

After reading and signing the consent form, the participants were asked to privately fill in three questionnaires: the Autism Spectrum Questionnaire, the Aggression Questionnaire and the McGill friendship questionnaire (Flynn et al., 2018). Then, both participants were escorted to the hyperscanning laboratory. They were installed separately, each in front of a screen and keyboard, in two adjacent rooms separated by a wall with a double glass window (86 x 178 cm) covered on both sides by a removable curtain. The curtain remained open during the EEG setup. It was closed during the pictures presentation and shortly re-opened during the pauses. Particular attention was paid to prevent any communication between the two participants. As far as we know, there was no way for them to be aware of the change of condition between the two blocks. In this study, we call "H1" the participants in the room on the right from the experimenters' point of view, and "H2" the participants in the room on the left. This factor will be called the participant's *designation* in the rest of this thesis. Two experimenters would install the EEG setup and give the instructions. One experimenter was assigned to the same participant for the length of the experiment.

After finishing the setup of the EEG headsets, the curtain was drawn and the participants were informed that they would see pictures of faces and were given the following technical instructions: avoiding all movements, sitting comfortably to avoid muscular tension, looking at the center of the screen, and prioritizing the pauses between two pictures to blink when needed. A ten-trials-long test was done to ensure that they had understood those instructions.

Then, the participants were instructed that their task was to try and memorize as many faces as they could, and that in the meantime they should try to feel in the presence of their partner. We described the second task to the participants in the following manner: they should keep in mind that their partner and they were doing the experiment together, despite not being allowed to communicate with or see each other. They were also told that they would see pictures different than their partner's. The memory task was chosen in previous JPE experiments because decision-making tasks were too distractive. The lights inside of the room were dimmed during the experiment and the door closed, except during the pauses. Before the start of the experiment, announcements were shown on the screens, reiterating the instructions. We recorded continuous EEG from both participants.

Experimental session

The experiment consisted of a single session including the two blocks: different-image and same-image. The experiment was divided into four parts, identical in length (i.e. number of trials) and separated by short pauses. The first two parts corresponded to the different-image block, and the third and fourth parts corresponded to the same-image block. The number of each type of trial was similar in all four parts.

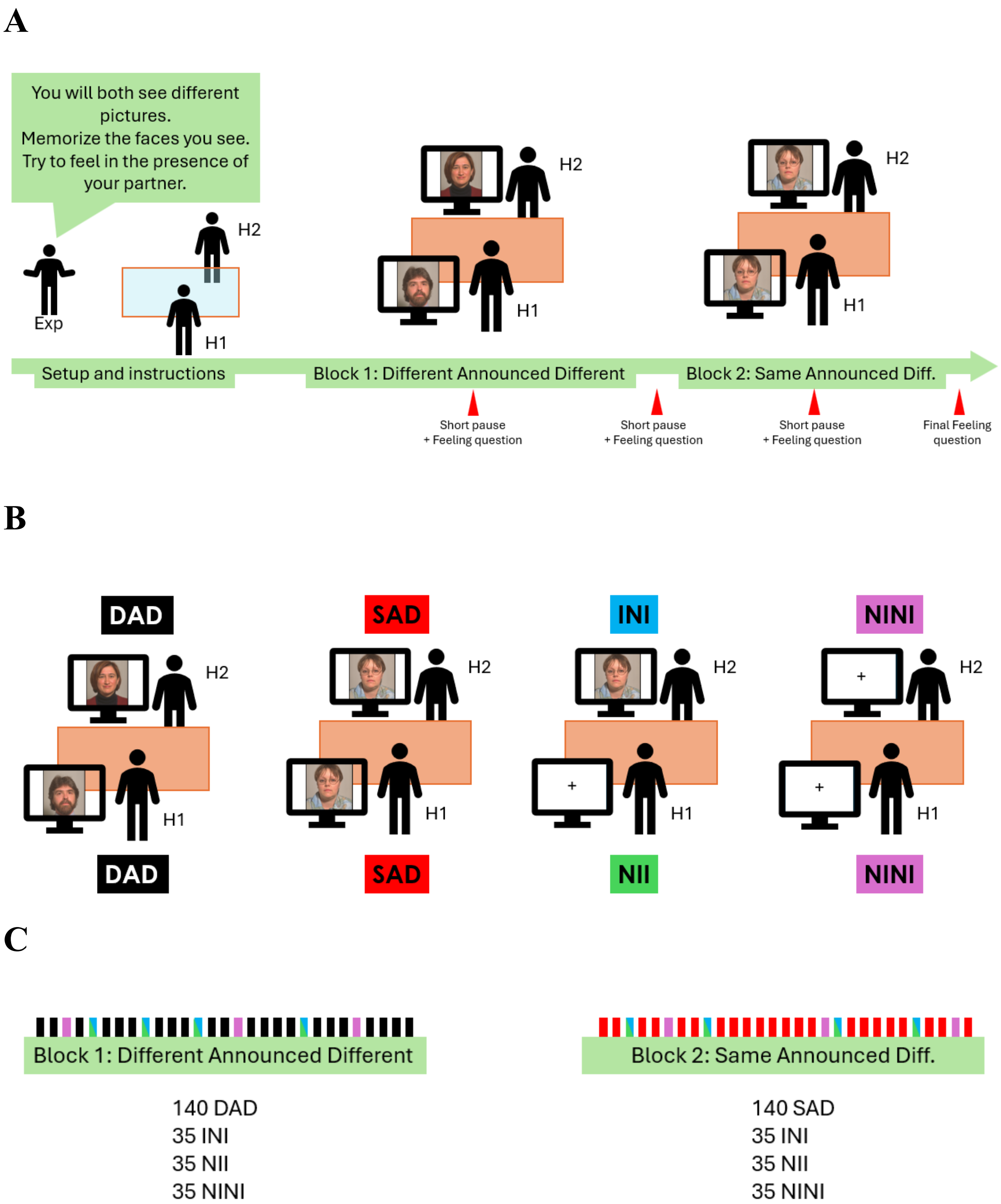

Figure 7 – Detailed of procedure and schematic illustration of the different types of trials. (A) Detailed timeline of the experiment. The two participants were installed in two adjacent rooms -not represented for readability-, separated by a window. The transparent blue rectangle represents the window without the curtain. The opaque orange rectangle represents the window with the curtain closed. (B) Detail of the four types of trials and corresponding conditions for the participants. DAD: Different announced different. SAD: Same announced different. INI: Image no image. NII: No image image. NINI: No image no image. (C) Schematic representation of the pseudo-random order of the stimuli within each block and number of trials.

Before each pause, a text was automatically displayed on the screen of both participants, asking them whether they had felt in the presence of their partner or not. The instructions were phrased as follows: *Please press "1" for option 1 or press "2" for option 2. Option 1: I felt in the presence of the other person for 50% or MORE of the time during which I saw the last 75 pictures*. *Option 2: I felt in the presence of the other person for 50% or LESS of the time during which I saw the last 75 pictures*. The participants could answer by pressing one of the two keys of their keyboard labelled "1" and "2". Then, the experimenter asked them to answer the same question with a thumb up or down for the video record. Only once both participants had answered did we open the curtain shortly. The participants could see each other but were not allowed to communicate about the experiment. After the fourth and last part, the participants were asked to answer the "Feeling in presence" question one last time before we removed the EEG headset. Participants who reported having felt in the presence of their partner strictly more than 50% of the total time of the experiment (i.e. three or four "MORE" answers) were categorized as the Felt Together (FT) group, whilst participants who reported having felt in the presence of their partner for 50% or less of the time (i.e. two or more "LESS" answers) were categorized as the Felt Alone (FA) group.

Debriefing session

Upon finishing the experiment, the participants were escorted back to the office room, where they could wash their hair before privately completing the last questionnaires. They were instructed not to talk about the experiment with each other during that time. They completed three questionnaires: the Peterson's Delusion Questionnaire, the Schizotypal Personality Questionnaire and a Debriefing Questionnaire. The Debriefing Questionnaire addressed technical aspects of the experiment, the strategy applied by the participant to fulfill the tasks, and their overall impression of the experiment.

Data acquisition

The electroencephalogram (EEG) was recorded from each participant using a 32-tin-electrodes elastic headset from Electro-Cap International. The electrodes positions included Fp1, Fp2, F7, F8, F3, F4, Fz, Fc1, Fc2, Fc5, Fc6, Fcz, T7, T8, C3, C4, Cz, Cp1, Cp2, Cp5, Cp6, P3, P4, P7, P8, Pz, Tp9, Tp10, O1, O2, Po9, Po10, along with the reference electrode on the right earlobe and the ground electrode (AFz). The electrodes were placed according to the modified expanded 10-20 system (The American Electroencephalographic Society, 1994). **Figure S1** shows their locations on the scalp. Each cap is connected to a separate set of four amplifiers. For all amplifiers, high- and low-pass filter half-amplitude cut-offs were set at 0.1 and 100 Hz, respectively. The high-pass filter half-amplitude cut-off was initially set at 0.01 but we were forced to use a more restrictive one because of a constant shift of low amplitude. EEG signals were amplified at a gain of 20,000 and digitized online at a 256 Hz sampling rate. For each pair, data was stored in a single file with 72 channels (2 x 32 electrodes + 8 trigger channels) that was later divided into two .ERP files, one for each participant.

Offline data processing

The 72 channels of the continuous EEG were separated between the two participants and 31 electrodes were used for the processing (Fcz was left out). EEG epochs starting 200 ms before the stimulus onset and ending 1000 ms after were extracted from the continuous EEG. The baseline of each of these epochs was set by computing the mean voltage value from -200 ms to the onset of the stimulus and by subtracting this value from each point of the whole EEG epoch. We then used the MATLAB toolbox EEGlab (version 2021.1) (Delorme & Makeig, 2004) to reject EEG epochs contaminated by artifacts. An EEG epoch would be rejected either if it showed a flatline persisting for more than 100ms or if its amplitude exceeded +/- 75 µV. Because the electrode sites nearest to the eyes (Fp1/2, F7/8) are more sensitive to eye movements, the amplitude threshold was increased to +/- 100 µV for those specifically. A channel was recalculated by interpolating nearby channels if it showed more than ~30% of epochs rejection. If it was impossible to obtain more than 50% of kept trials without recalculating more than 6 channels, the participant would be rejected. Epochs were averaged for each type of trial to obtain the corresponding ERPs. We divided the INI trials between those happening during the different-picture block (INID) and those happening during the same-picture block (INIS). We obtained one file per participant of every pair, with ERPs calculated for all 31 electrodes for each condition. Grand averages ERPs were computed using the ERPs of all participants. Mean voltages were measured from the ERPs of every participant in the three time-windows of interest (200-300 ms, 350-550 ms, and 600-900 ms) at every electrode.

We were concerned that the addition of no-image-type control trials (NII and NINI) would impact the image-type trials (DAD, SAD, INI). Indeed, this would create two kinds of inter-stimulus-intervals: short ISI (1 x ISI = 200 to 1200 ms), and elongated ISI (2 x short ISI + 1 no-image-type trial = 1400 to 3400 ms). Due to the number of each type of stimulus, DAD and SAD trials were more likely to follow a long ISI than INI trials (see **Figure S2**). To ensure none-biased within-block comparison, another pre-processing pipeline was designed to discriminate between image-type trials that followed another image-type trial (Post-image, PI) and those that followed a no-image-type trial (Post-No Image, PN).

Analyses

Statistical analysis first consisted of mixed-model repeated-measures ANOVAs using a multivariate approach on IBM-SPSS (version 29.0) and JASP (version 18.3) to compare the ERPs of participants.

A first ANOVA aiming at investigating between-blocks effects included the three time-windows (200-300 ms, 350-500 ms, 600-900 ms), all electrodes (31 levels) and the two main conditions (DAD/SAD) as within-subjects factors and the reported feeling of presence (FT/FA) and the participant designation (H1/H2) as between-subjects factors. We added the distinction between H1 and H2 because we were wondering about a potentially lateralized effect depending on whether the participant had their partner on their left or their right. Indeed, we ask them to *Feel in the presence* of their partner, a feeling that we have yet to precisely characterize. We suspected that *feeling in presence* might translate into keeping one's partner in the mental attentional space of the participant. Given the experimental setup's symmetry, such an attentional strategy might be correlated with a lateralized neural effect, hence the addition of the H1/H2 factor in the analysis to control for such an effect. We used the Greenhouse-Geisser (1959) adjustment in case of sphericity violation, and corrected F- and p-values are given at every relevant time in the results section. Upon verification for interactions, subsequent ANOVAs were run for specific groups. We used the Bonferroni correction to assess p-values in the post-hoc tests. In case of significant interactions between the factor electrodes and another factor, t-tests were run at all electrodes levels, and the electrodes showing the strongest size effect were used to present differences between groups. A False Discovery Rate correction (Benjamini & Hochberg, 1995) will be applied at level 0.05 on p-values for analyses at the electrode level.

Other ANOVAs were run to investigate within-block effects, i.e. comparison between the main conditions (DAD/SAD) and the corresponding control conditions. Visual inspection revealed that the NII and NINI conditions only showed resting-state-like signals and were similar to one another (see **Figure S3**). Consequently, the analysis of control conditions was focused on the INI trials.

Then, we ran mixed-model repeated-measures ANOVAs using 4-parts separated data. This separation would allow us to control for the impact of the time throughout the experiment independently from the change of condition in the middle of the session. Using the natural division of the session into four parts, we computed four chronologically ordered ERPs. Within-subject factors were the 4 parts corresponding to the main conditions (DAD1, DAD2, SAD1, SAD2) and the 31 electrodes, and the between-subject factors were the feeling of presence (FT/FA) and the participant designation (H1/H2).

Expected outcomes

According to previous studies, we expected the ERPs corresponding to the DAD condition to be more negative than the ones corresponding to the SAD condition. We expected this effect mostly in the participants who would report having felt together during the experiment. Given that the INI condition is close to a "different-picture" type of trial, we expect the ERPs corresponding to the INI condition to be closer in voltage to those of the DAD condition.

Results

Out of our 40 participants, 30 (16 H1) reported having felt in the presence of their partner for strictly more than 50% of the experiment. This gave us a satisfactory cohort for the FT group. On the opposite, the FA group only counted 10 participants. Thus, some effects might not appear significant in the FA group because of the small number of participants. Observed tendencies and interactions will thus be cross-checked through visual inspection. **Table S1** presents the proportion of accepted trials for the three picture-type kinds of trials (DAD/SAD/INI), which were all above 75% in average and similar across groups.

Different-picture vs Same-picture blocks

Figure 8 shows the grand average ERPs of the 40 participants for the DAD and SAD conditions. The SAD-evoked ERPs presented more positive values than the DAD-evoked ones. This effect was observed for most of the stimuli duration and at most electrode sites.

A mixed-model repeated-measures ANOVA was conducted to evaluate whether the participants' ERPs for the main condition varied significantly between the first and second block, whether this effect would vary depending on the time-window and electrode, and whether it was influenced by the feeling of presence (FT/FA) and the participant's designation (H1/H2). Normality was assumed due to our large cohort (n=40). The analysis revealed a significant main effect of the factor Block ($F(1,36) = 4.633$, $p = 0.04$) and a significant three-way interaction between the factors block, Feeling and Designation ($F(1,36) = 5.924$, $p = 0.02$).

The analysis revealed a significant interaction between the factors Block and Electrodes ($F(3.740,134.654) = 3.091$, $p = 0.02$) and a significant three-way interaction between the factors Block, Feeling and Electrodes ($F(3.740,134.654) = 4.319$, $p = 0.003$). However, the analysis revealed no significant interaction between the factors Block and Window. Simple effect analysis showed that the difference in mean voltage between DAD- and SAD-associated ERPs was not significant in H2 participants (FA and FT) and in the H1/FA sub-group and was only significant in H1/FT sub-group ($F(1,28) = 26.237$, $p = 1.25E-4$). **Table 1** presents the results of this analysis.

Post-hoc tests using the Bonferroni correction showed that DAD-ERPs were more negative than SAD-ERPs in this subgroup ($M = -1.108$ µV, $d = -0.395$, $t(29) = -4.791$, $p_{bonf} = 7.948E-4$). **Figures 9 & 10** present the scalp maps showing the SAD-DAD difference separated by feeling and by designation respectively (see **Figures S4 & S5** for the grand averaged ERPs separated by feeling of presence).

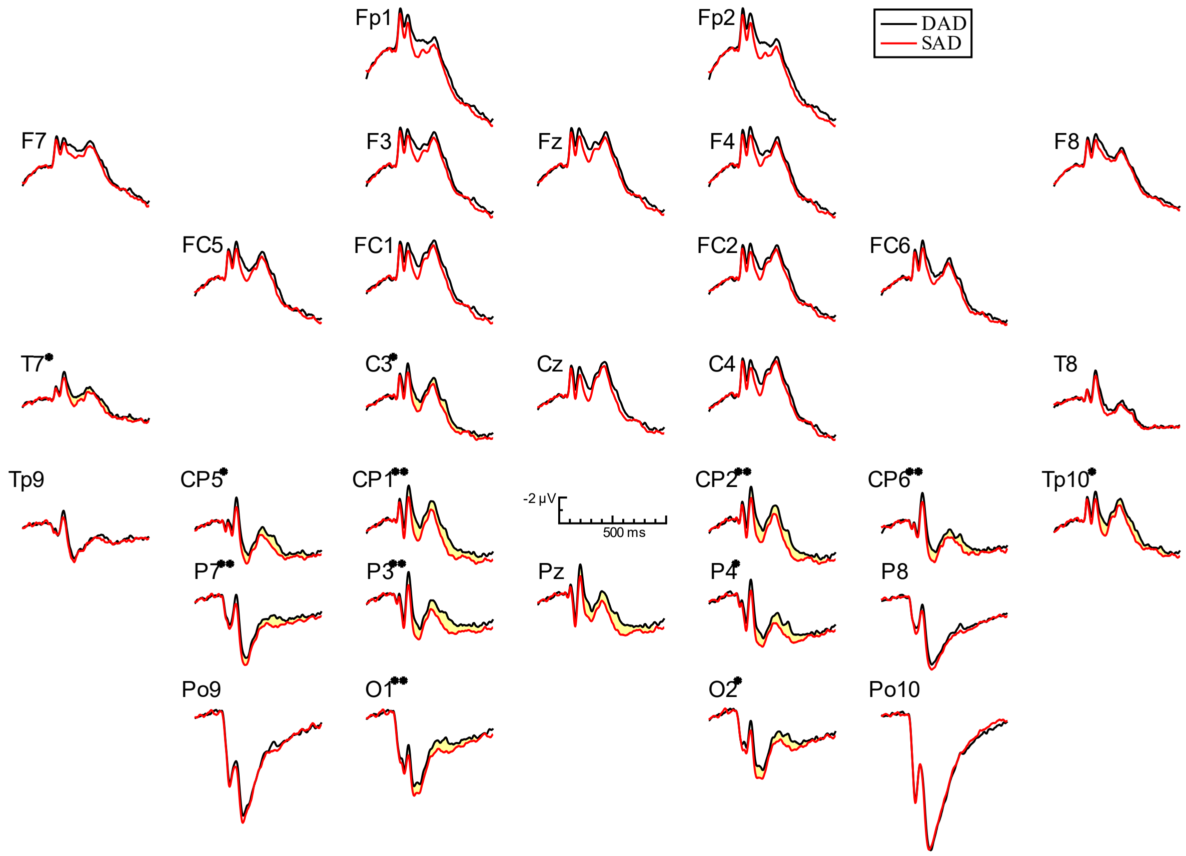

*Figure 8 – Grand average ERPs (n=40) of the main conditions separated by block. Voltage is represented on the y-axis (microvolts), the x-axis represents time from stimulus onset in milliseconds. Stars indicate a statistically significant difference of the mean voltages on highlighted time-window (two-tailed t-test: *p<0.05, **p<0.01)*

Simple Main Effects - Block

Designation	Feeling	Sum of Squares	df	Mean Square	F	p
H1	FA	1.371	1	1.371	0.024	0.886
	FT	913.631	1	913.631	26.237	1.251e-4
H2	FA	60.609	1	60.609	1.109	0.340
	FT	0.076	1	0.076	0.002	0.964

Table 1 – Results of simple main effect analysis on the block difference differentiated between the four sub-groups determined by the between-subject factors: H1/H2 x Felt-together/Felt-alone.

Post-hoc paired samples two-tailed t-tests were performed at the electrode level. Most electrodes showed a significant difference between the DAD and SAD mean voltages within the FT group (24/31, up to 28/31 if restricted to H1), whereas only P3, P7, Cp6 and O1 showed significant differences in the FA group. Using an FDR of 0.05, the results remained for the FT group but no electrode showed significance in the FA group.

The observed effect was in the predicted direction with DAD-ERPs being more negative than SAD ones. Finding it only in an FT sub-group was consistent with our a priori hypotheses, but the restriction to the H1 participants might indicate an experimental bias – the origin of which will be discussed later in this thesis. Moreover, the wide localisation and the absence of restriction to a specific time-window were not consistent with previous results, notably those using the MED bank. Furthermore, the effect appeared to dim in the late time-window, whereas the JPEs were maximal in the LPP in some prior studies.

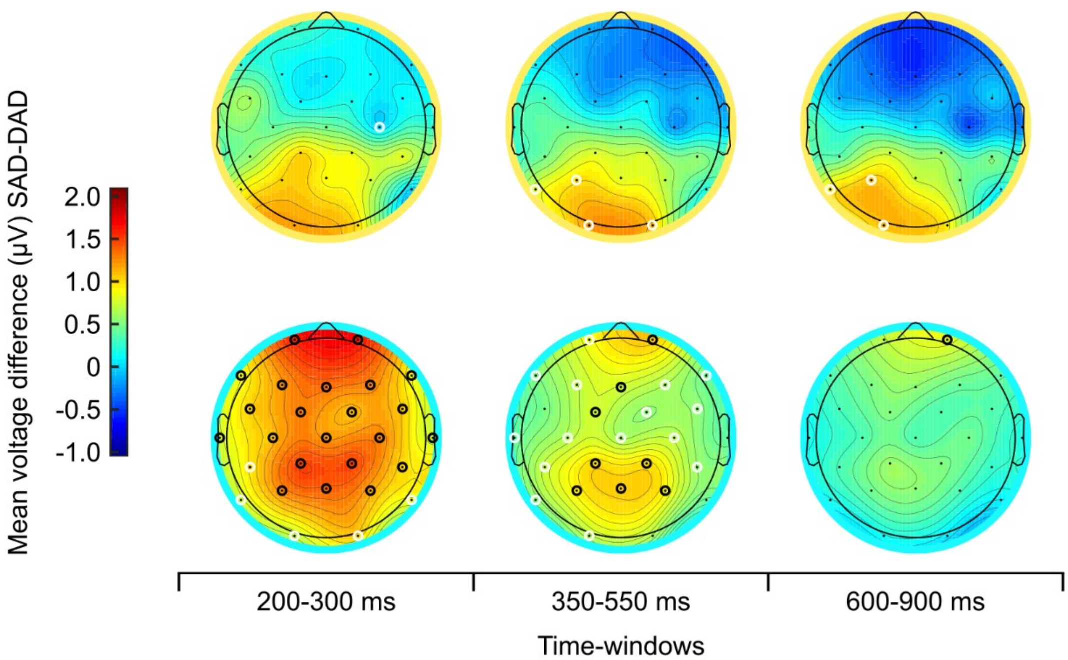

Figure 9 – Scalp maps showing the mean voltage difference between the two conditions (SAD-DAD), separated by reported feeling of presence (yellow outline = FA, blue outline = FT) Circles indicate a significant difference from 0 at paired sample t-test (white : p<0.05, black : p<0.01)

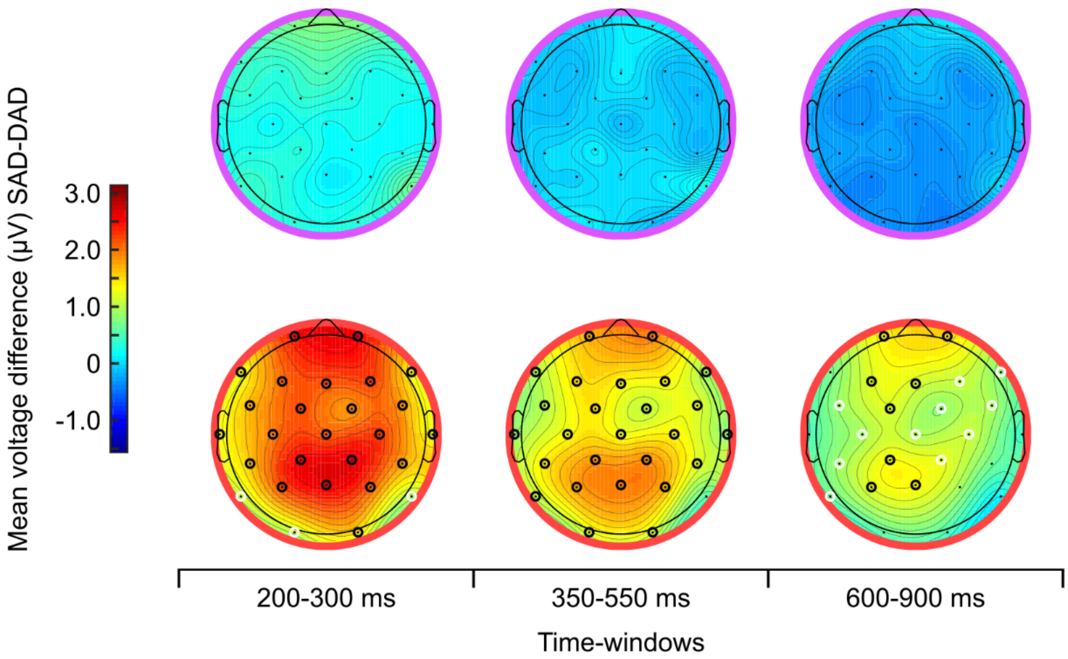

Figure 10 – Scalp maps showing the mean voltage difference between the two conditions (SAD-DAD), separated by designation, restricted to FTs (red outline = H1, purple outline = H2). Circles indicate a significant difference from 0 at paired sample t-test (white : p<0.05, black : p<0.01)

Within-block differences

We know that a bigger proportion of the DAD and SAD trials occurred after an elongated inter-stimulus interval (38.5% of the trials) than the INI trials do (15,8% of the trials). Thus, it appeared necessary to control for the impact of the ISI duration on the ERPs before proceeding to legitimate within-block comparisons.

Impact of inter-stimulus-interval on main and control trials

An alternative pre-processing pipeline was used to differentiate between the trials that followed another picture-type trial (Post-Image, PI = short ISI) and the ones that followed a no-picture type of trial (Post-No image, PN = long ISI). **Figure 11** shows the grand average ERPs of the DAD condition for the 40 participants divided between PI and PN trials. ERPs following an elongated inter-stimulus interval (ISI) presented more positive voltages than the ones following a short ISI. This observation applied to all picture-type trials, as shown in

Figure 12 for the 200-300ms time-window at the electrode Pz (see **Figure S6, S7 & S8** for the ERPs corresponding to the difference conditions).

In light of these results, within-block analyses were performed on the PI and PN trials separately to ensure relevant comparisons between main conditions and controls (DAD vs INID / SAD vs INIS).

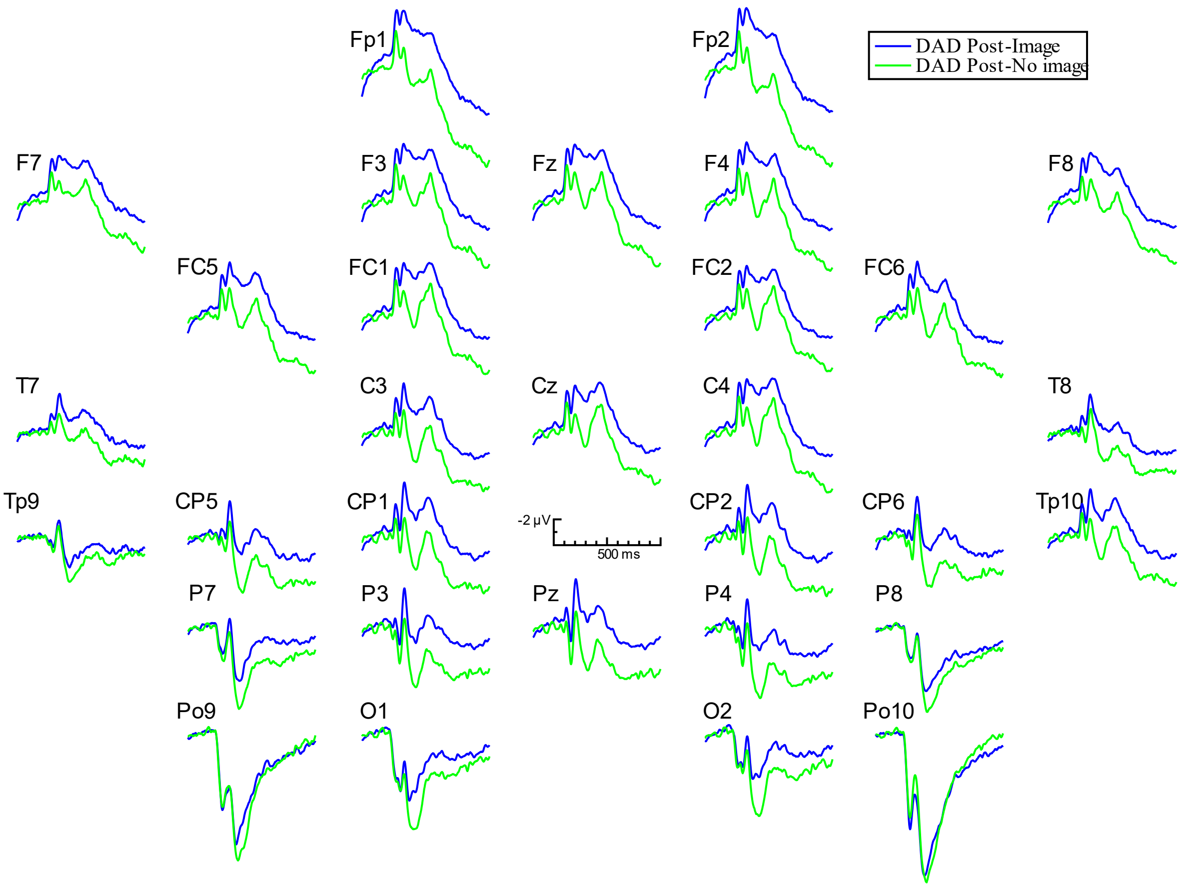

*Figure 11 - Grand average ERPs (n=40) of the DAD trials separated by length of ISI before the trial: trials happening after a short ISI in green (DAD-PI), trials happening after a long ISI in blue(DAD-PN). Voltage is represented on the y-axis (microvolts), the x-axis represents time from stimulus onset in milliseconds. Stars indicate a statistically significant difference in the mean voltages (two-tailed t-test: *p<0.05, **p<0.01)*

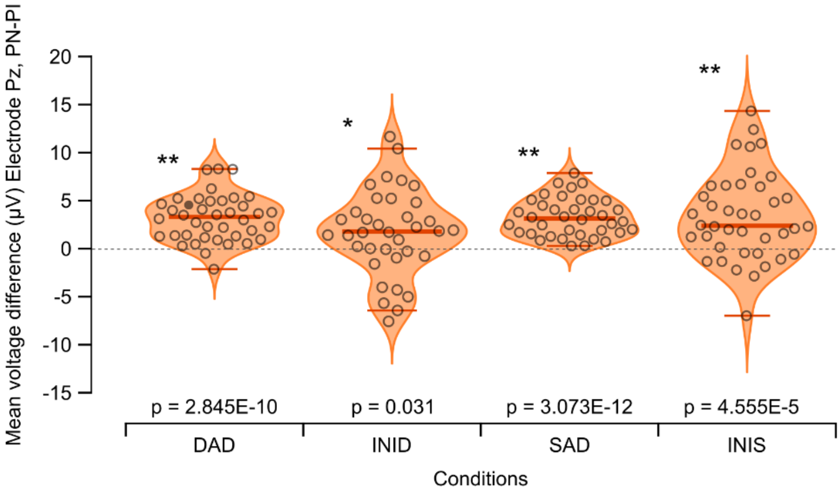

*Figure 12 – Violin plot: difference between the mean voltages of Post-Image and Post-Noimage trials (PN-PI) for all subjects (n=40) on the 200-300ms time-window at the electrode Pz. Similar observations are made at the other time-windows and electrode sites. Stars indicate a statistically significant difference from 0 (two-tailed t-test: *p<0.05, **p<0.01).*

Within-block comparison

A mixed-model repeated-measures ANOVA was run to determine whether there was a difference between the mean voltages of the DAD (PI only) and INID (PI only) conditions. The within-subject factors were the conditions (DAD/INID), the three time-windows and the electrodes. The between-subjects factors were the Feeling (FT/FA) and Designation (H1/H2). The analyses showed no significant difference between the mean voltage of the DAD-ERPs and the INID-ERPs ($F(1,36) = 0.046$, $p = 0.831$). No interaction was observed.

A similar ANOVA aiming at comparing the mean voltages of the SAD (PI only) and INIS (PI only) conditions also reported no significant differences between the SAD- and INIS-ERPs ($F(1,36) = 0.418$, $p = 0.522$).

Two identical ANOVAs were performed for the PN trials. The comparison between the SAD-PN and INIS-PN ERPs mean voltages revealed no differences between the two conditions ($F(1,36) = 0.327$, $p = 0.571$). No significant main effect of the factor Condition was found in the DAD-PN vs INID-PN analysis ($F(1,36) = 0.897$, $p = 0.350$), but a significant difference was observed between the two conditions exclusively for the H2 group on the third time-window ($F(1,36) = 4.558$, $p = 0.042$) on a post-hoc analysis after observation of an interaction between the factors Condition, Designation and Window. However, the high specificity of these results and the very low number of trials used for the calculation of the PN ERPs raise strong doubts about the importance of this difference. **Figure 13** summarizes those observations by presenting the Main-Control voltage difference before and after separation of the PN and PI trials (see **Figures S9 to S14** for the corresponding ERPs).

In conclusion, it appeared that the INI trials did not evoke different ERPs from the DAD/SAD trials and are affected by the block difference as well. Consequently, they cannot be used as a form of baseline ERPs.

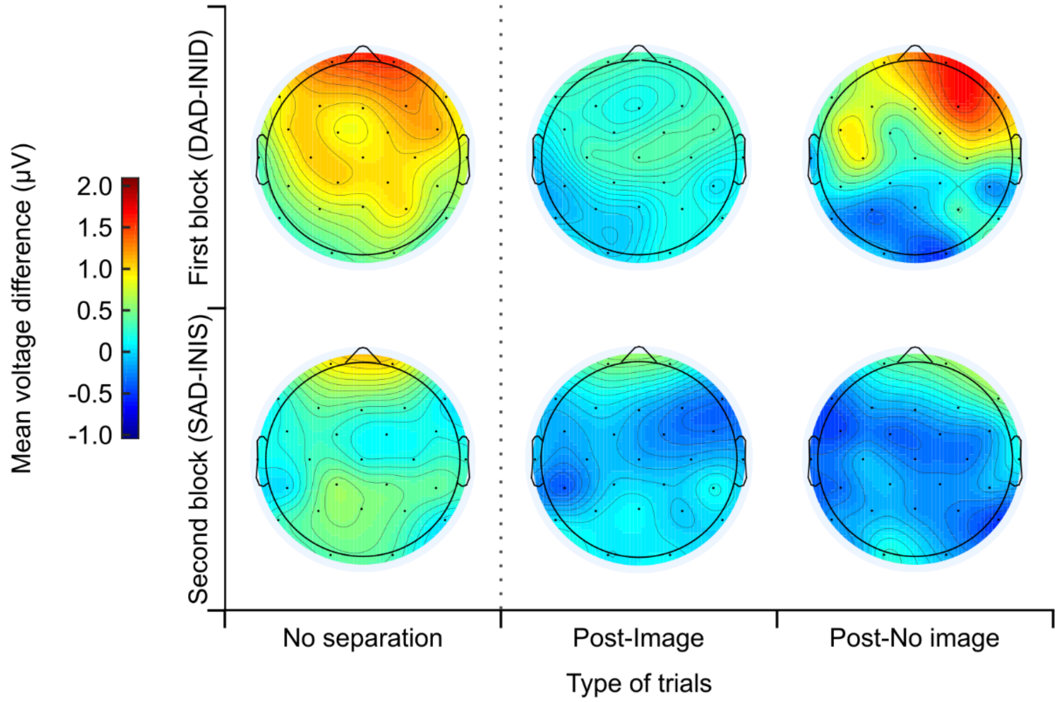

Figure 13 – Scalp maps of the mean voltage difference between the main condition (DAD/SAD) and the control trials (INID/INIS) for all subjects (n=40) on the 200-900ms time-window, before and after separation of the Post-Image and Post-No Image trials.

Intermediate discussion on the within-block analyses

As seen above, the INI trials did not differ from the DAD/SAD trials. The INI-associated ERPs (INID and INID) differed from the first vs. the second blocks and followed the tendency of the main condition, thus showing the same effect that we had observed between the DAD and SAD condition. That the main and control conditions display the same pattern raised questions on the nature of the effect. While the DAD and SAD trials were technically different, the INI trials were identical throughout the whole experiment, and yet both were similarly affected. Two opposing hypotheses had to be considered: on the one hand, the control conditions within each block might have been influenced by the global strategy dictated by the main and therefore did not elicit a differentiated pattern. Previous authors have indeed argued that the observation of JPEs were associated to a specific cognitive state that would take time to develop, explaining the absence of JPEs in mixed designs. In our design, the main condition (DAD or SAD) remained predominant within each block. We counted on this majority of DAD/SAD trials to enable the development of the neural strategies, but it might be that once in a certain cognitive state, all stimuli were treated similarly. On the other hand, adding the controls could also created a form of mixed design within each block, which would have prevented the strategy from developing as it should, as was observed by Tardif et al. (2019), obliterating JPEs at the same time. Therefore, the risk remained that the difference between the two blocks was not a JPE but in fact caused by a bias which would have impacted the main condition and the controls indifferently.

Between-block effect in-depth analysis

To control for an effect of the order of the blocks independent from the change of condition, we designed a new pre-processing pipeline to treat separately the four parts of the experiment instead of just separating the two blocks. The corresponding conditions were labelled DAD1, DAD2, SAD1 and SAD2, respectively. We used the actual division of the experiment in four parts with pauses between the parts, so that all parts corresponded to a similar experimental context (see **Figure 14**). This allowed us to control for evolutions throughout a block.

Figure 15 shows the grand average ERPs of the 40 participants for the main conditions with the four-parts division. DAD1-ERPs stood out upon visual inspection as more negative than the ERPs of three other conditions. This effect was observed for most of the epoch's duration and on most electrodes. The three other curves seemed nearly indiscernible. As thus, the observed effect did not seem related to the DAD/SAD dichotomy. Separation by between-subject factors reiterated the earlier observations (see **Figures S15 to S18** for the ERPs separated by between-subject factors). Only the H1/FT sub-group presented this effect in a generalized manner, whereas the three other sub-groups showed no clear evolution of the ERPs over time. Interestingly, in the FA group, a small number of electrodes presented a similar yet weaker difference between DAD1 and DAD2. **Figure 16** represents the difference in mean voltage between successive parts for the different subgroups at Pz.

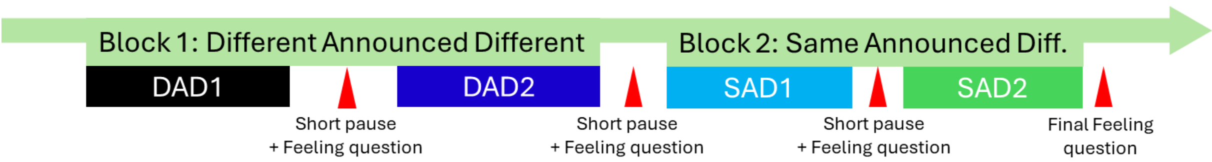

Figure 14 - Schema illustrating the chronological four-part division of the experimental session. The colours are the same as used for the wavelines in Figure 14.

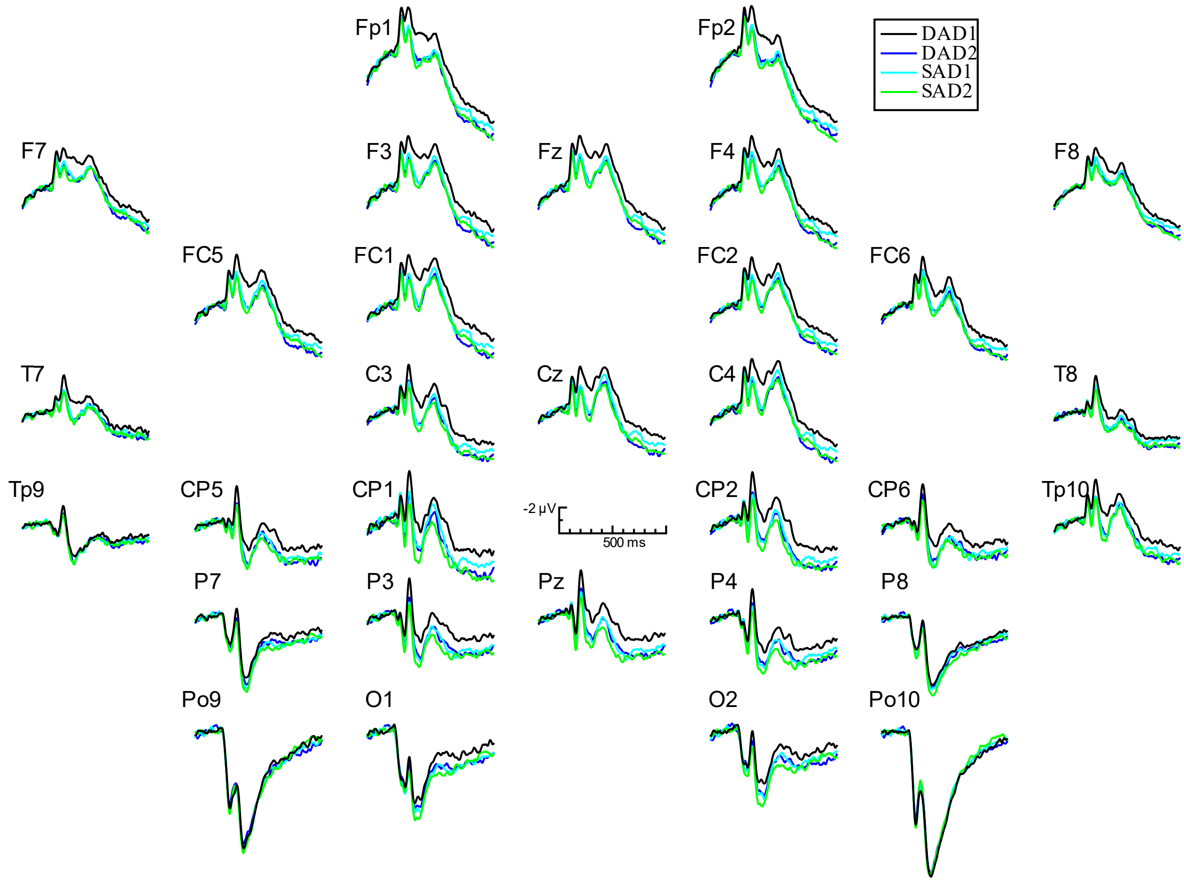

Figure 14 - Grand average ERPs (n=40) for the main condition throughout the four parts of the experiment. Voltage is represented on the y-axis (microvolts), the x-axis represents time from stimulus onset in milliseconds.

Intermediate discussion on the impact of the order

No difference was observed between the DAD2-ERPs and SAD1-ERPs in the four-part analysis, suggesting that there was no electrophysiological response to the change of condition. The analysis demonstrated that the ERPs evoked by the different-picture block (DAD1+DAD2) were drawn to more negative values by the earliest trials, i.e. the DAD1 part. This suggested that the higher negativity of the DAD block was only caused by it being presented first and that a reversed order would cause a reversed effect. What we had taken for JPEs seemed to be an effect of the order of the blocks However, Jeuland et al. (2022) had come to different conclusions when assessing this possibility.

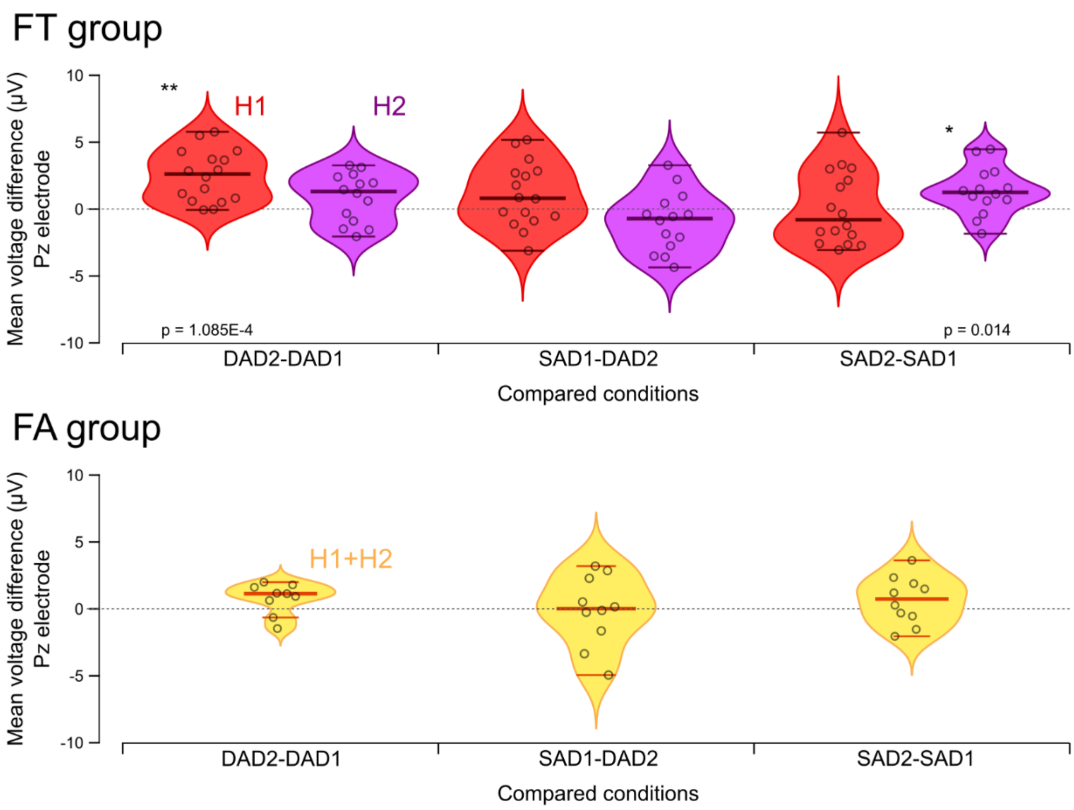

*Figure 16 - Violin plot: Mean voltage difference between the successive parts of the experiment (Second-First, Third-Second, Fourth-Third) for the 200-300ms time window, main conditions only (DAD1, DAD2, SAD1, SAD2), separated according to the reported feeling of presence and designation within the FT group. Similar observations are made at the other time-windows and electrode sites that showed significant between-block differences. Stars indicate a statistically significant difference from 0 (two-tailed t-test: *p<0.05, **p<0.01).*

Our design was based on the observation by Calmels et al. (2023) that reversing the order did not give a reversed effect but suppressed it. They had concluded that the effect was not caused by the order of the blocks. To bring light on this contradiction, we decided to run retrospective analyses to see whether a similar effect of the order was found in their data too, in which case the real interrogation would be regarding its absence with the reversed design.

Retrospective analysis of Jeuland et al.'s data

The analyses presented in Calmels et al. (2023) numbered a total of 81 participants distributed as follows: 43 of them had been shown the different-picture block first and the same-picture block after (DAD-first). The other 38 participants had been tested with the reversed order (SAD-first). As in our experiment, the pairs ignored that there were two blocks. Our preliminary work was focused on the DAD-first group as they had been exposed to conditions similar to ours. We then compared the two groups to assess the impact of the order.

All the ERPS of this section were obtained using pre-processing pipelines identical to the ones developed for our data, merely adapted for the 28-tin electrodes headset used by Jeuland et al. (2022). We applied the same processing parameters: threshold for artifact detection, recalculation methods of electrodes and exclusion criteria in case of too many rejected electrodes, etc. Notably, we had to exclude two participants from the analyses because a full hemi-scalp had to be recalculated for them, despite Jeuland's archives stating that they had been kept in their grand averages. Consequently, our newly computed ERPs present slight differences from those computed by Jeuland et al. However, these differences remained extremely marginal.

Preliminary analysis

A 4-part analysis similar to the one presented earlier was run using Jeuland et al.'s data. The 24 pairs of participants considered here belonged to the DAD-first group. Thus, they had experimental conditions similar to our participants. **Figure 17** presents the resulting grand averaged ERPs. Once again, the DAD1-ERPs presented a more negative voltage than that of the next three parts, which doubtlessly participated in creating the between-block difference. Visual inspection of the grand averaged ERPs separated by feeling of presence confirmed that the effect was found only in the FT group and not in the FA (ERPs grand averages for those groups are shown in **Figures S19 to S22**). However, in this dataset, no clear difference was observable between the H1 and the H2 participants, as well as between the subgroups FT/H1 and FT/H2.

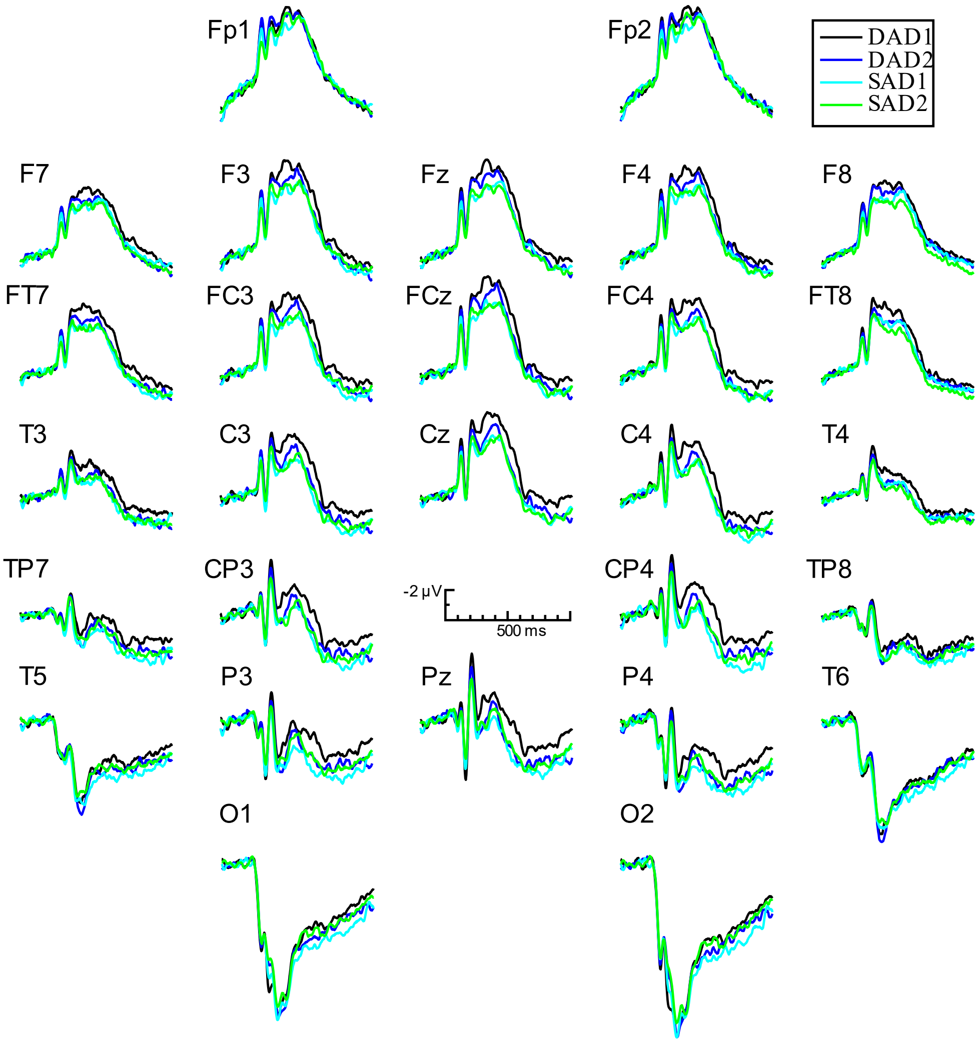

Figure 17 - Grand average ERPs (n=48) for the main condition throughout the four parts of the experiment, DAD-first Felt-together subgroup. Data from Calmels et al.'s collection. Voltage is represented on the y-axis (microvolts), the x-axis represents time from stimulus onset in milliseconds.

This preliminary analysis confirmed our intuition that the effect of the order observed in our data wasn't new. This motivated us to investigate the source of this effect more deeply. Notably, interrogations remained as to why Calmels et al. (2023) had not observed the effect in the participants who had been presented with the SAD block first. Moreover, we aimed to determine the biases that could have misled their original interpretation of the data.

Results

The impressive pool of 81 participants recorded for Calmels et al.'s (2023) study actually comprises distinct series of recruitment. At least three different teams of experimenters have participated to the experiment, which brings its share of issues regarding the repeatability. The most concerning division within the pool revolves around the last 9 pairs. Those participants were recruited to increase the pool of participants after preliminary analyses had been conducted. Notably, it had been observed that the FT participants elicited much stronger effect, and this observation was the main motivation for the additional recruitment. This could have led to experimenter biases linked with expectation – we will discuss those potential biases in a later part of this thesis. What is concerning for a study of the impact of the order is that the additional participants were all tested with the DAD-first setting; therefore, they have no SAD-first counterparts that would have been tested simultaneously and under similar experimental context. In Calmels et al.'s analysis, the additional participants account for 12 out of the 25 participants of the DAD-first/FT grand average, whereas the SAD-first group consists only of participants from the older series of recruitment. Consequently, it seemed necessary to investigate the impact of the order using a strictly balanced pool of DAD-first and SAD-first participants tested under the same conditions. However, this was also an interesting occasion to look for the electrophysiological differences that may have arisen between the two series of recruitment.

Characterizing the additional pool of participants

We assessed if the additional participants (Add group) elicited deviations from the rest of the pool by comparing the electrophysiological effects observed in this group to those observed in the original pool of participants (Ori group). **Figure 18** shows the mean voltage difference between the SAD and DAD conditions over the scalp in both pools, restricted to the DAD-first/FT subgroup – all the participants of the Add group reported having felt in the presence of their partner (see **Figure S23 & S24** for the grand average ERPs separated by condition).

In the original pool of participants, an effect was observed at occipital and parietal electrode sites over the medium (350-550ms) and late (600-900ms) time-windows. The additional participants presented a fronto-central effect which was already present in the early time-window (200-300 ms) and lasted until the latest one. The central component of this effect seemed to dim over time, whereas the frontal component showed no variation.

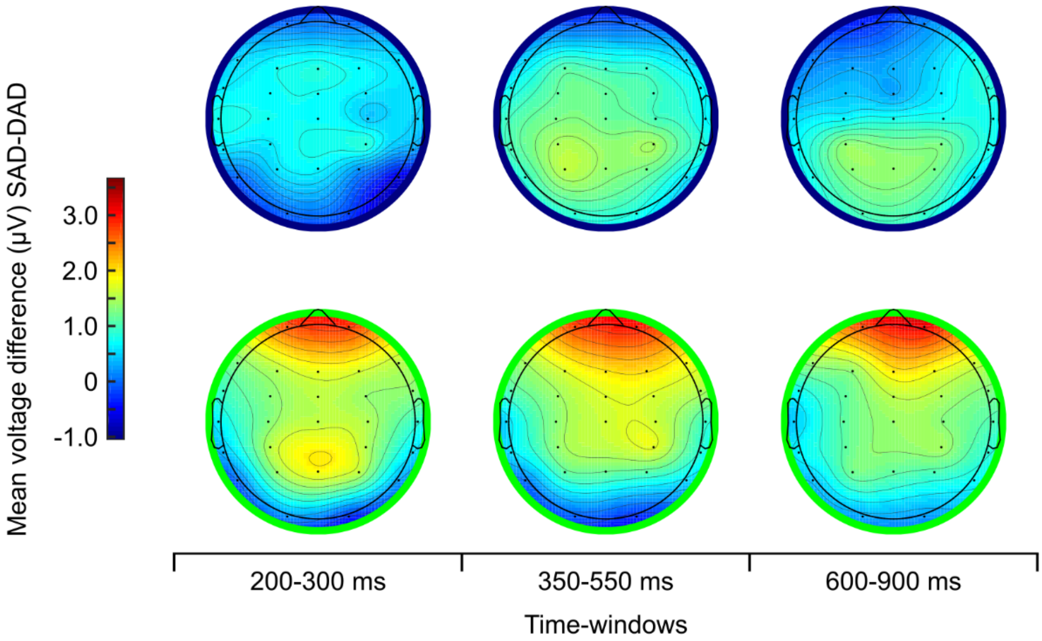

Figure 18 – Scalp maps of the mean voltage difference between the two conditions (SAD minus DAD) over the three time-windows of interest, DAD-first/Felt-together subgroup, separated between the Original pool (top, blue outline, n=12) and the Additional pool (bottom, green outline, n=16). Data from Calmels et al.'s collection.

The two pools of participants presented an effect in the same direction, with the SAD-associated ERPs being more positive than the DAD ones. The effect was thus in the expected direction of the JPEs; however, it was more widespread and of greater amplitude in the additional pool than in the original pool. Therefore, the addition of the additional pool of participants leads to a strengthening of the already present effect at the parietal electrode sites and creates an effect at fronto-central sites (see **Figure S25** for the evolution of the SAD-DAD voltage difference before and after inclusion of the additional pool). Given the similarity in terms of time windows and localisation, we suspected that the frontal effect in Jeuland et al. (2022) had been caused by the same temporal bias that caused the effect in our experiment. This temporal bias seemed to have gone bigger in the additional set, and we will detail the suspected origin of this effect and the causes of its increase in the discussion part of this thesis. In the following part, we present our analysis on the effect of the order including only participants from the original series of experiments of Jeuland et al. (2022).

Balanced comparison between conditions & effect of the order

Once the additional participants were excluded from the pool, we were left with 14 DAD-first/FT participants and 19 DAD-first/FA participants. To run analyses properly balanced regarding the order of the blocks factor, we randomly chose an equal number of SAD-first participants for each subgroup.

Figures 19 & 20 present the grand averaged ERPs for the two experimental conditions balanced for the order, i.e. averaged between the DAD-first and SAD-first groups, for the FTs and FAs separately. No difference between the DAD and SAD conditions was observed at any site for the FA participants. A difference between the two conditions was observed in the FT group at occipito-parietal sites, with more positive SAD-evoked ERPs than the DAD-evoked ones. This difference appeared around 300ms after stimulus onset and remained until the late components. Unlike what had been found by Calmels et al. on the DAD-first group only, our balanced ERPs showed no fronto-central effect for the FT participants.

Figures 21 & 22 present the grand averaged ERPs of the first and second blocks without distinction of the experimental condition, i.e. a chronological separation of the ERPs.

DAD-first and SAD-first participants were mixed, FTs and FAs were separated. The FT group's waveform plot presented a fronto-central effect characterised by the ERPs of the first block being more negative than those of the second block. No difference was observed at occipito-parietal sites. No effect was observed in the FA group except for the most frontal electrodes – which are known to be sensitive to artifacts such as eyes movements.

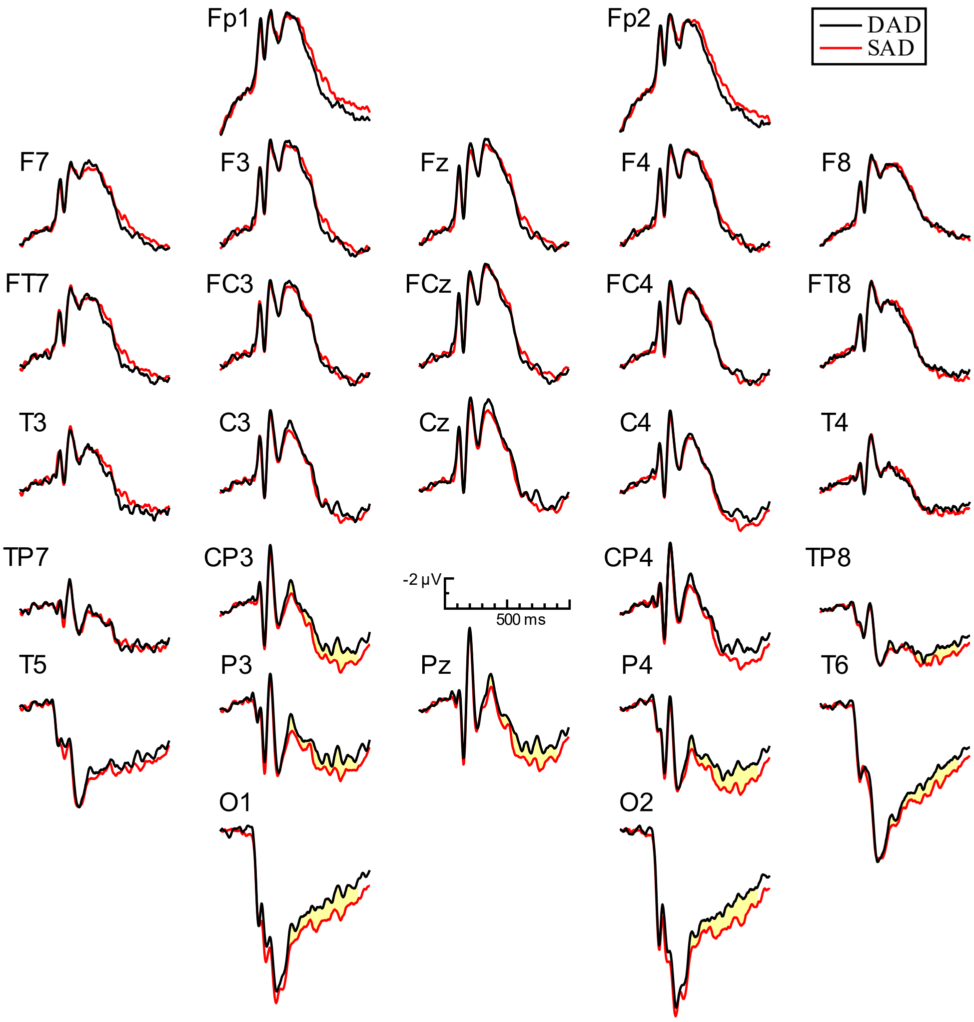

Figure 19 - Grand average ERPs (n=28) of the two main conditions balanced between DAD-first (n=14) and SAD-first (n=14) participants, Felt-together group. Data from Calmels et al.'s collection. Voltage is represented on the y-axis (microvolts), the x-axis represents time from stimulus onset in milliseconds. Yellow area indicates a significant difference between the two conditions on the highlighted time-windows, paired sample t-tests (p<0.05).

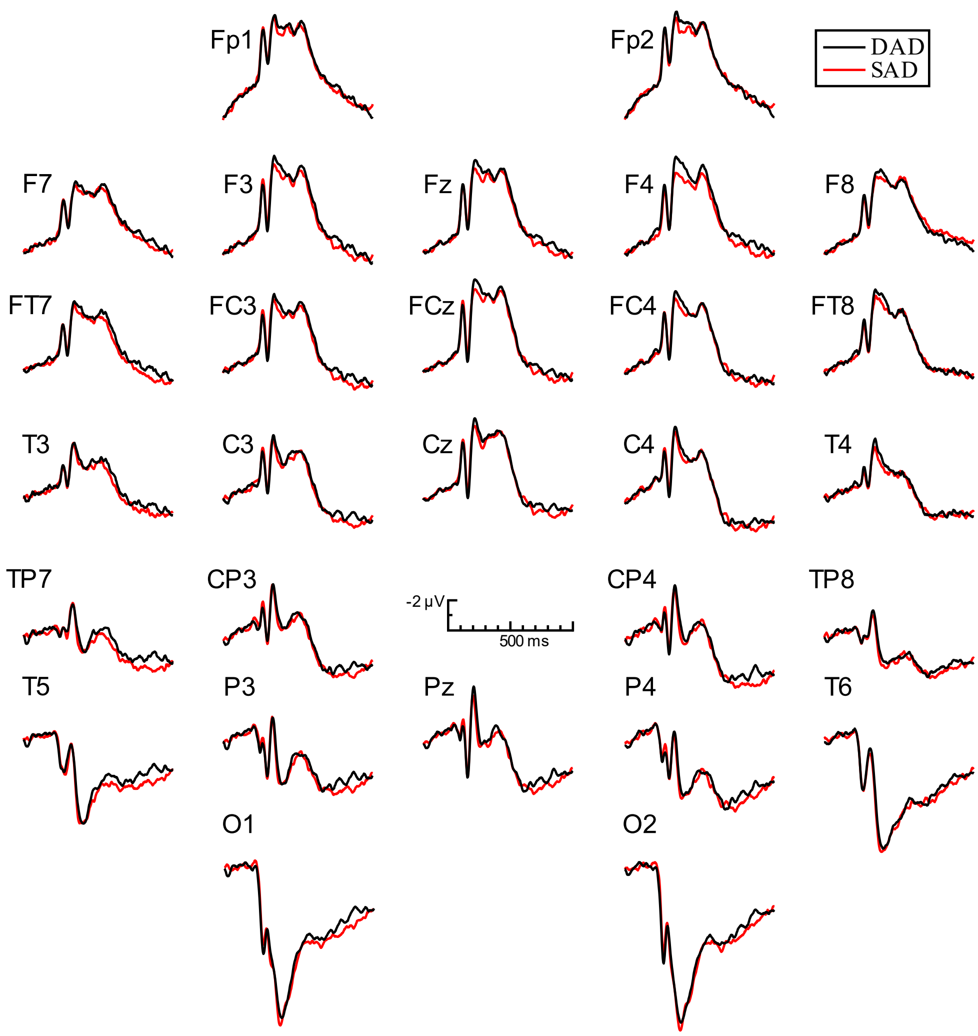

Figure 20 - Grand average ERPs (n=36) of the two main conditions balanced between DAD-first (n=19) and SAD-first (n=19) participants, Felt-Alone group. Data from Calmels et al.'s collection. Voltage is represented on the y-axis (microvolts), the x-axis represents time from stimulus onset in milliseconds. Yellow area indicates a significant difference between the two conditions on the highlighted time-windows, paired sample t-tests (p<0.05).

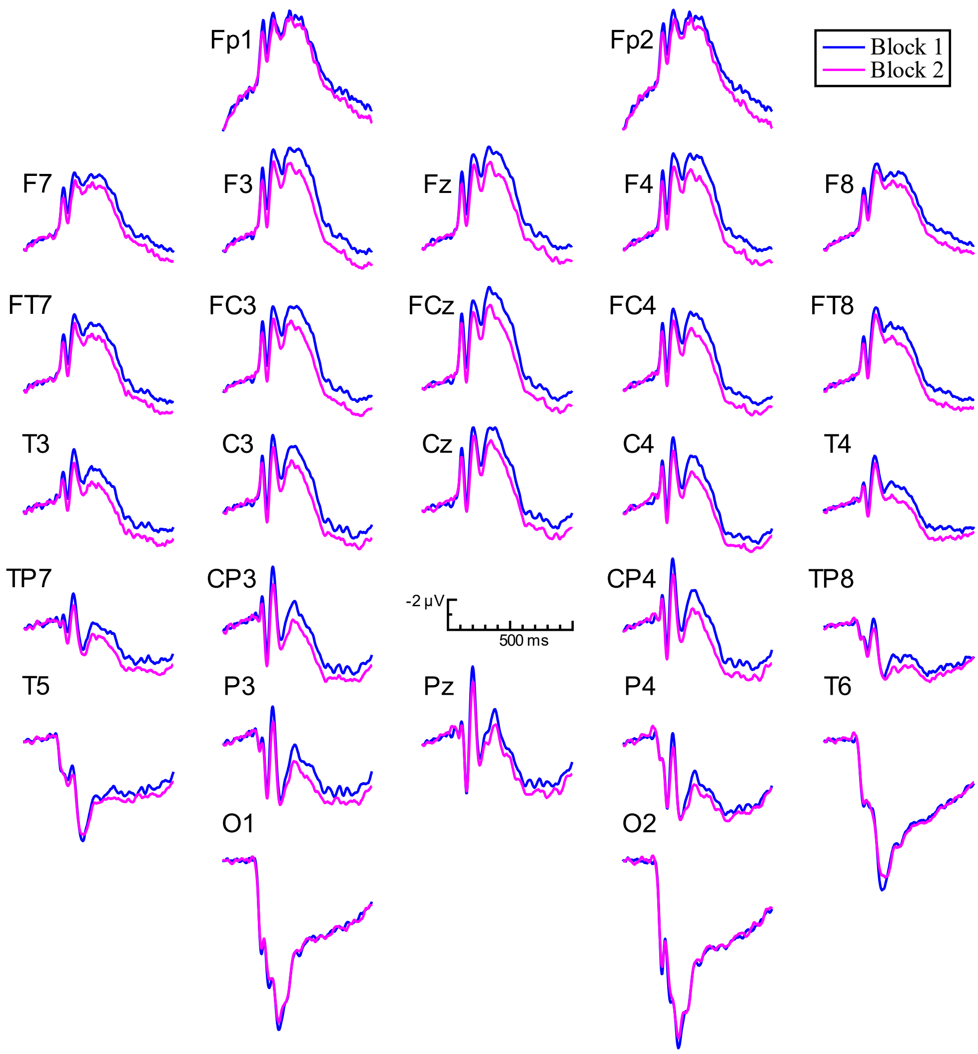

Figure 21 - Grand average ERPs (n=28) of the first and second block balanced between DAD-first (n=14) and SAD-first (n=14) participants, Felt-together group. Data from Calmels et al.'s collection. Voltage is represented on the y-axis (microvolts), the x-axis represents time from stimulus onset in milliseconds.

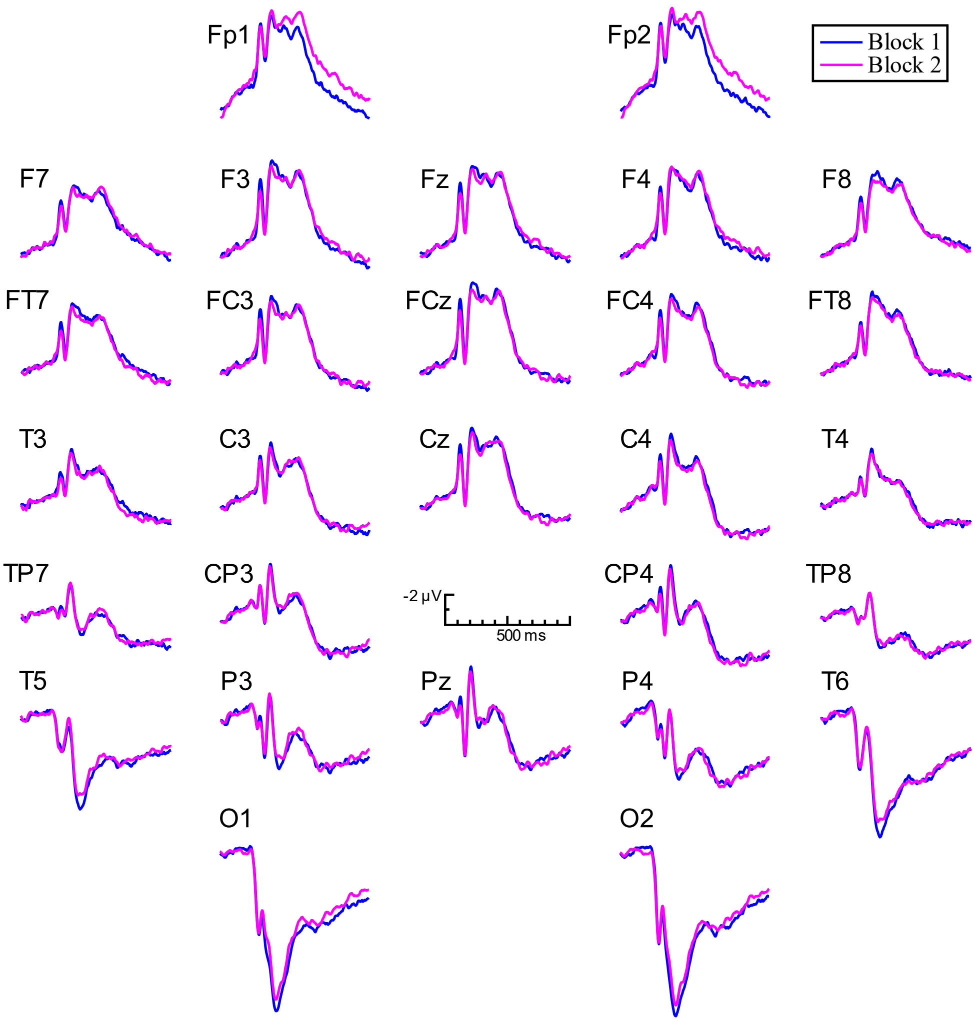

Figure 22 - Grand average ERPs (n=36) of the first and second block balanced between DAD-first (n=19) and SAD-first (n=19) participants, Felt-Alone group. Data from Calmels et al.'s collection. Voltage is represented on the y-axis (microvolts), the x-axis represents time from stimulus onset in milliseconds.

Those observations suggested the superposition of two different effects in the data, both interacting with the feeling of presence: a fronto-central effect correlated with the order of the blocks, and a JPE-oriented effect at occipito-parietal sites, correlated to the change of condition between DAD and SAD.

We also proceeded to a visual inspection of the grand averaged ERPs of the two FT sub-groups separately (DAD-first and SAD-first). The waveform plots revealed differences between the ERPs evoked by the DAD and SAD conditions at many electrode sites in both groups (see **Figures S26 & S27** for the waveform plots). However, the two effects observed earlier were discernable upon comparison of the two plots. At fronto-central sites, the block appearing first always evoked more negative ERPs, giving the impression of a JPE effect – i.e. DAD more negative than SAD – for the DAD-first/FT subgroup, and the reversed effect – i.e. SAD more negative than DAD – for the SAD-first/FT subgroup. Consistently with the aforementioned balanced grand averages, at occipito-parietal electrode sites, both subgroups showed an orientation of the effect classic of JPEs; that is, for the SAD-first group, an effect in opposition to that observed at fronto-central sites. Moreover, no difference was observed at parietal sites in the SAD-first subgroup, marking a frontier between the JPE-oriented effect and the inverted effect at centro-frontal sites. The inversion of the fronto-central effect between the two subgroups was characteristic of an effect of the order, whereas the occipito-parietal effect seemed decorrelated from the order, confirming the relevance of using balanced grand averages. The following analysis were run on the complete balanced pool of participants in order to characterize the second, JPE-like, electrophysiological effect.

Omnibus mixed-model repeated-measures ANOVAs were conducted for the time-windows of interest (N400: 350-550ms, LPP: 600-900ms) to evaluate whether the participants' ERPs varied significantly with the sameness of the picture, and whether this effect would vary depending on the electrode sites, and whether it was influenced by the feeling of presence (FT/FA). The factor order of the blocks (DAD- or SAD-first) was added to the analysis as the waveform plots had shown it to be a factor of influence to the variances. However, the participant's designation (H1/H2) was not considered in those analyses as visual inspections had shown no impact of it.

On the N400 time-window, the analysis revealed a significant interaction between the factors Sameness and Electrodes ($F(3.616, 224.195) = 3.639$, $p = 0.009$) and a three-way interaction between the factors Sameness, Feeling and Electrodes nearly reached significance ($F(3.616, 224.195) = 2.475$, $p = 0.051$).

On the LPP time-window, the analysis also revealed a significant interaction between the factors Sameness and Electrodes ($F(3.743, 232.075) = 4.957$, $p = 0.001$) and a marginally significant three-way interaction between the factors Sameness, Feeling and Electrodes ($F(3.616, 224.195) = 2.487$, $p = 0.048$).

Post hoc ANOVAs were run for the FT and FA groups separately. A significant interaction was found between the factors Sameness and Electrodes in the FTs ($F(3.438, 92.829) = 4.136$, $p = 0.006$) but not in the FAs ($F(3.868, 143.112) = 0.914$, $p = 0.455$) for the 350-550 ms time window. Similar results were observed on the 600-900 ms time-window, with a significant Sameness x Electrode interaction found in the FTs ($F(4.642, 114.525) = 6.556$, $p = 4.47E-5$) but not in the FAs ($F(3.372, 124.729) = 1.138$, $p = 0.339$)

Post-hoc paired samples one-tailed t-tests were then performed within the FT group at the electrode level. The alternative hypothesis was that the SAD-ERP would be more positive than the DAD one. In the FT group, several electrodes showed significant differences between the DAD and SAD condition on either one or both time-windows. However, many comparisons did not reach significance after a p-value correction using FDR at level 0.05. The results of these t-tests are summarised in **Table 2**.

One-tailed T-Test

		t	df	p	Cohen's d	Cohen's d SE
N400 /350-550ms	Pz	1.963	27	3.0E-02	0.371	0.195
	P4	2.244	27	1.7E-02	0.424	0.197
	P3	1.948	27	3.1E-02	0.368	0.195
	T6	2.521	27	9.0E-03	0.477	0.199
	CP3	1.987	27	2.9E-02	0.376	0.196
	O2	2.844	27	4.0E-03	0.537	0.202
	O1	**3.379**	**27**	**1.0E-03**	**0.639**	**0.207**
LPP /600-900ms	Pz	2.159	27	2.0E-02	0.408	0.197
	P4	**3.086**	**27**	**2.0E-03**	**0.583**	**0.204**
	P3	2.117	27	2.2E-02	0.4	0.196
	T6	**3.661**	**27**	**5.4E-04**	**0.692**	**0.21**
	TP8	2.476	27	1.0E-02	0.468	0.199
	CP3	2.392	27	1.2E-02	0.452	0.198
	O2	**4.615**	**27**	**4.3E-05**	**0.872**	**0.222**
	O1	**3.96**	**27**	**2.5E-04**	**0.748**	**0.214**

Table 2 – Results of one-tailed paired samples t-tests on the voltage difference between the two conditions of Sameness. Felt-together group only, balanced for order of the blocks. n=28. Bold: p-values verifying the critical criteria after FDR (0.05).

Discussion

This study's first aim was to replicate the Joint Processing Effects, observed for the first time by Bouten et al. (2014). The JPEs have been observed in subsequent studies as well, that also improved the experimental design to limit the risk of behavioural biases. Those studies had found a difference between the ERPs produced during the different-pictures and the same-pictures block, with the latter showing more negative values.

We followed an "optimal protocol" combining the observations of the previous studies. Our second goal was to assess the robustness of this protocol and to provide constructive feedback on the conditions when needed.

To better understand the electrophysiology of these effects, we also added a control condition where only one of the two partners sees a picture and one where both are shown a fixation cross for the length of a stimuli.

Finally, we have collected behavioural data to help in the understanding of this effect. Notably, we hoped to better characterize how our participants understand the self-reported "feeling of presence", which correlates with the observation of JPEs in the most recent studies.

Overall summary of the results

We found a significant difference between the ERPs evoked by the stimuli of the first and second blocks in the FT group. However, this effect did not present the same spatial and temporal characteristics as in prior studies. Our results did not show any influence of the time-window, whereas JPEs were mostly observed in the N400 and LPP time-windows in previous studies. Even though localizations would vary between studies, those using the MED Bank of stimuli had not shown an effect as widely spread on the scalp as our results do. Moreover, our effect correlated with whether the participant was sitting on the left or on the right during the experiment, which was a new observation, and hinted at the possibility of behavioural bias.

To test the impact of the order of the blocks, we divided each block into two equal and successive parts, for a total of four parts chronologically ordered. Would the difference between the two blocks be caused by the change of condition between DAD and SAD, one would expect to find an outstanding difference between the ERPs of the second and third part. Our analysis revealed that the observed difference between the two blocks was due to a greater negativity of the DAD1 half-block compared to the three other parts. Upon visual inspection, the ERPs evoked by the no-picture-type trials (NII/NINI) did not show any difference between the four half-blocks, which ruled out material biases such as a cooldown of the amplifiers (see **Figures S28 & S29**). Thus, the observed effect was not caused by the change of condition in the middle of the experiment, but by a higher negativity in the earliest trials.

We were especially surprised to find a parasite effect caused by the order of the block, as Calmels et al.'s results not only had ruled out the risk of a bias due to the order, but they had claimed that there was an optimal order, i.e. having the DAD-block first. As we suspected an irregularity in their data, we re-ran their analysis whilst excluding a subgroup of the DAD-first participants who had been tested during a delayed series of experiment with no SAD-counterparts, since we were concerned that methodological biases could have caused this additional pool to diverge from the original. Our preliminary 4-part analysis of Calmels et al.'s data had revealed the presence of an effect dependent on the order of the blocks. The effect was similar to the parasite effect found in our data, with the first block's ERPs being more negative than the second block's. Thus, we computed grand averaged ERPs of the DAD-first and SAD-first groups together to correct this bias. Using a balanced pool of participants, were able to find significant differences between the ERPs evoked by the DAD and SAD conditions that were not correlated with the order of the blocks. These effects were found at occipito-parietal sites. In conclusion, the discovery of the parasite effect of the order in our data allowed us to retrospectively identify an issue in a previous study, whose correction has permitted the identification of significant JPE-like effects. However, in our data, only the effect of the order was observed. In the following part, we will suggest modifications to the "optimal protocol" that we initially followed, as well as hypotheses to explain the pattern of the parasite effect. Then, we will explore further areas of investigations offered by our observations, and we will address the matter of the physical mechanism underlying JPEs.

Comments on the "optimal protocol"

The "optimal protocol" is a set of experimental conditions supposed to produce the strongest JPEs: two closely related partners are shown pictures of faces, separately and simultaneously. They are asked to memorize the faces and to feel in the presence of their partner without being able to communicate. They are told that the pictures will be different for the two of them, which is true during the first block of the experiment but not during the second, where the pictures are the same for both participants.

The results of our experiment and the re-treatment of previous data have raised points of reflection regarding those conditions.

1) When a block design is used, the order of the blocks should be strictly balanced from one pair to the next. The use of a block design exposes the data to contamination by a parasite effect of the order, with an increased negativity of the ERPs of the block coming first. Depending on the order, this effect can either increase or diminish the amplitude of proper JPE-like effects, or even be misinterpreted as JPEs. The computation of balanced grand

averages is enough to get rid of this effect. Contrary to what was originally suggested by Calmels et al., using a specific order in a block design does not elicit stronger JPEs.

2) A direct consequence of this observation is that further studies should gather all the control trials in a separate block. Indeed, in our experiment, the attempt to mix the Image-No-Image (INI) control trials failed at eliciting ERPs different from those evoked by the main conditions (SAD/DAD). Moreover, in our data, no JPE-like effect seemed to have occurred, and only the parasite effect due to the order was observed, whereas the two effects were intermixed in Calmels et al.’s data. We suggest that the inclusion of INI trials within the DAD and SAD blocks has created an involuntary mixed design as in Tardif et al. (2019), despite the predominance of the main conditions, hence the absence of JPE-like effects. In the future, studies aiming at determining a “baseline ERP” to better characterize the JPEs should not mix the control trials with the main conditions, but instead have a control block. Whilst balancing the order of all blocks between the pairs of participants will remain necessary to correct for a potential effect of the order, the ERPs evoked by INI trials should not vary depending on the place of this control block in the session, as they do not for the DAD and SAD conditions.

3) Even though we only used one kind of announcement, that is, that the pictures would differ, this experiment was another occasion to assess the possibility of deceit by the participants. As far as we know, our setup eliminates all possibilities for the participants to become aware of the change of conditions between the first and second block by themselves. In prior studies, this was verified by asking the participants whether they had felt deceived at any moment during the experiment. The same question was asked in our debriefing session, and the only participants who reported feeling deceived explained that they expected a memory test at the end of the experiment. None of them mentioned the possibility that the experimenter could have lied about the sameness of the pictures. However, we cannot entirely rule out the possibility that the experimenter unconsciously influenced the participant at some point.

Indeed, our results show a strong correlation between the observation of the effect of the order and the designation (H1/H2) of the participants. The observation of the effect was restricted to the H1 participants. We suggest that the determining factor in the designation is the assigned experimenter, as the same experimenter did the setup and gave the instruction to either all the H1s or all the H2s. The H1/H2 difference led to a complete obliteration of the effect, where we expected at the most a lateralization of some components. The room being organised in an exactly similar merely symmetrical way, it seems highly unlikely that the left/right difference would lead to the full disappearance of the effect. Moreover, previous studies where the experimenter would often switch sides had never shown any H1/H2 difference. We hypothesize that the two experimenters might not have put the same emphasis on different parts of the instructions, unconsciously leading to differences in mindsets between the H1 and H2 participants. Although they put an earnest effort in giving the instruction neutrally and in a standardized manner, one cannot completely erase its own accent, gender, personality, or expectancy, which have been shown to influence participants in behavioural research (Rosenthal, 1963, Pillette et al., 2021, Atwood et al., 2022, Pierre et al., 2023). Although it is an impact on the parasite effect that is discussed in our case, this observation raises concerns regarding the potential impact of the experimenters on the JPEs as well. Future studies should use a double-blind design to ensure that the experimenter won't unwillingly provide the participants with clues regarding the sameness of the pictures and the veracity of the announcement.

4) Although our data don't present JPE-like effects but only the effect of the order, we observed an influence of the self-reported feeling of presence. Like for JPE-like effects, the effect of the order is observed more significantly by participants who reported feeling in the presence of their partner. We see this as an opportunity to better define how the "feeling of

presence" is perceived by the participants whilst providing a behavioural explanation for the effect of the order.

The effect of the order is characterised by more negative ERPs during the early trials. A shift towards more positive values in ERPs has been previously correlated with higher focus or increased cognitive activity in the literature (Petrenko, 2008). Interestingly, we do not observe a continuous evolution as would be expected for a habituation effect (Segalowitz et al., 1997, Renoult et al., 2012) but rather a brutal change between the first and second half-block. Moreover, we observe a global positive shift, whereas habituation or fatigue effects generally pertain to specific components (e.g. in Bonnefond et al., 2010). Besides, it was shown that participants' motivation wasn't likely to decrease if they expected to be evaluated (Bonnefond et al. 2011). Consequently, our electrophysiological observations do not adhere to a loss of attention.

We rather suggest that the effect of the order indicates a change of state of mind as the participants adopt specific cognitive strategies. The participant's answers in the debriefing session revealed that "feeling in the presence of one's partner" was perceived as a task requiring active thinking rather than a passive sensation. Furthermore, when asked whether they had used a strategy to memorize the faces, many participants reported a memorizing strategy that integrated a "feeling in presence" dimension, such as imagining their partner's reaction to the picture. As the questions regarding the memory task had to be answered before accessing the part about the feeling of presence, we can assert that this strategy was predominant enough for them to think of it spontaneously. Most participants reported in the debriefing session having adopted a routinized strategy to memorize the many faces, so we suggest that the development of a strategy at the beginning of the experiment explains the observed difference in the ERPs. At the beginning of the experiment, the participants might still be figuring out a method to complete the two tasks – memorizing and feeling in presence

– and thus present a more versatile attention. Once a strategy has been found and adopted, the participants' focus may become more stable. A smaller division of the blocks would be necessary to identify the characteristic length of the effect. It could also help us evaluate the impact of the pauses on the ERPs. However, smaller divisions imply fewer trials per ERPs, hence more noise, which is why we only dealt with four parts in this thesis.

The strategy hypothesis is consistent with the interaction between the electrophysiological effect of the order and the Feeling factor: the participants who found a strategy, and therefore presented the electrophysiological effect, were naturally more likely to report having felt in the presence of their partner. We argue that the electrophysiological effect does not characterizes the feeling of presence but rather the participant's efforts to feel in presence. Preliminary analyses aiming at comparing the FT and FA groups in Calmels et al.'s data have found very localised differences between the two groups. Namely, electrode sites T6 and Tp8 have shown significant differences between the ERPs recorded in the FT group and those recorded in the FA group (see **Figure S30**). A similar comparison in our data also revealed a significant difference between the ERPs of FTs and FAs at T6 and Tp8, but reversed (see **Figure S31**). These analyses in addition to our behavioral observations are a first step towards a better understanding of the Feeling factor and a better interpretation of its influence on social effects such as the JPEs, not as a consequence but rather as a cause of the neural observations.

Our comparative analysis of the additional vs. original pool of participants in Calmels et al.'s data provides a further insight into how the experimenter might influence the electrophysiological effect by influencing the participant's effort to feel in presence of their partner. The additional pool of participants presented a stronger fronto-central effect similar in nature to the effect of the order of the blocks; our strategy hypothesis suggests that this observation reflects a greater effort of the participants to find strategies to feel in presence of their partner. Our knowledge of the methodological context strongly supports this suggestion. Indeed, Jeuland et al.'s preliminary analysis on the original pool of participants had revealed that the FT participants elicited a stronger effect – we now know that the fronto-central part of it was in fact a bias due to the order. This is what motivated them to record additional participants to increase the number of FT; therefore, it is highly likely that they have put more emphasis on the instruction to *Feel in presence* during these supplementary sessions. As mentioned earlier, variations in the experimenter's expectation can lead to variations in the reports and behavioural results (Atwood et al., 2022). Accordingly, all additional participants declared to have felt in the presence of their partner, whereas the proportion was closer to 50% in the original pool. The desire to have more FT participants might have come through in the tone or the attitude of the experimenter, leading to more effort by the participants to fulfill this goal, probably through the development of strategies. The resulting increase in the DAD/SAD difference was interpreted by Calmels et al. as a success; in fact, our analyses revealed that it was mostly the parasite effect that has gone stronger, leading to the misinterpretation regarding the impact of the order of the block.

While the FT participants actually present stronger JPEs, it appears that insisting too much on the *Feeling of presence* strengthens the effect of the order as well. Even though the effect of the order can easily be corrected using balanced averages, harmonizing the instructions between sessions should also be a methodological focus of further studies.

Consequently, further work should build on our observations whilst assessing the robustness of other conditions such as the closeness of the participants or the impact of the announcement in order to provide the literature with a validated protocol. Finding a bias of the order where we expected none reminded us of the methodological rigour necessary when designing brand new experiments, but also when we base design on previous studies.

Further investigations and determination of a physical mechanism

Bouten et al.'s (2014) discovery of the effect was, above all, an unexpected surprise. However, they were not the first to hypothesize a physical substrate to consciousness exterior to the activity of the brain itself. Some authors had already formulated the idea of an electromagnetically supported network of consciousness (Pockett, 2000, Jones, 2013, but see McFadden, 2020 for more recent contributions), or even of percepts being encoded in the modulations of quantic fields (Hameroff & Penrose, 2014). Moreover, a growing body of studies shows the importance of electric fields for our brain, whether it is just sensitivity (Barett, 2014, Casarotto et al., 2022), or encoding of information within our brain in the form of electric fields (Pitnosis & Miller, 2022, Pinotsis & Miller, 2023).

However, although the first observation of JPEs led Bouten et al. to consider the electromagnetic hypothesis more seriously, the following studies – including this one – were focused on replicating the effect. The investigation of the underlying mechanism was left out, but some hypotheses have since been ruled out nevertheless. For instance, a possibility was that this interaction at a distance without communication would be achieved chemically through the emission of pheromones. The existence of pheromones in humans is highly debated (Wyatt, 2020), but the authors had to recognize that a chemical hypothesis was not more audacious than inter-brain electromagnetic communications and had to be considered. However, this hypothesis was not very fitting considering the timing, and it did not survive the separation of the participants in adjacent rooms by Tardiff et al. (2020).

More debates have taken place around the quantum entanglement hypothesis. On this deeply technical question, the Dr. Debruille had to rely on others, namely Pr. Gilles Brassard, Pr. Frank Prato and Pr. Cristophe Caloz who very kindly accepted to visit the laboratory and even to participate in the experiment at the time. All three refuted the idea that quantum entanglement might create such an effect, in the light of their own approach of the concept, and concluded that JPEs would have to be explained in the framework of electromagnetic fields (Benett et al., 1993, Binhi & Prato, 2018). The author of this thesis acknowledges his ignorance regarding those subjects and cannot provide arguments in favor or against the quantum entanglement hypothesis.

The electromagnetic hypothesis is, of course, very challenged, and needs to be assessed; however, testing this hypothesis constitutes a major challenge in itself. Indeed, according to the aforementioned physicists, the electromagnetic waves at play would be the very weak ones of extremely low frequency (i.e. 0.5 to 50 Hz). This range of electromagnetic waves is particularly hard to shield and can travel long distances, therefore electromagnetically isolating the participants or increasing the distance between them might not be enough to dismiss the effect. We recently suggested that electromagnetic interferences could be used to try and cut off the interaction; however, this suggestion raised more questions: in an EEG room full of electronic devices, how come the electromagnetic waves are not already jammed?

As the determination of a mechanism becomes a matter of prime importance, it also appears that this investigation will require knowledge on and understanding of physical phenomena above that of a cognitive neuroscientist. This exploratory work calls upon rigorous collaborations, to avoid methodological pitfalls and misconceptions across fields.

Conclusion

Our methodological approach of the "optimal protocol" designed to elicit Joint Processing Effects revealed that biases and erroneous interpretations had led to the design of a flawed protocol. In this study, we suggest corrections to the protocol and directions for further investigations. While we did not find JPE-likeeffects, we were able to identify a parasite effect of the order in our data and in older ones, to correct it and to refine previous results. We hope that this work will motivate further studies aiming at replicating the JPEs to continue having a critical regard on their methods and their hypothesis. Indeed, our work also raises many questions regarding these effects.

Since their first observation, JPEs were seen not only as an answer to the problem of similarity of percepts, but also as the revolutionary observation of a direct brain-to-brain interaction. Such a bold assertion cannot leave space for uncertainties. As we observed a strong influence of the experimenter on our results, it seems crucial to run double-blind studies to eliminate the risk of unconscious unveiling of information by the experimenter regarding the sameness of the picture.

This study illustrates the importance of the instructions and their interpretation by the participants, such as the Feeling of presence. While previous studies interpreted it as a passive sentiment, it now appears to be a form of active mentalization by the participants who adopt strategies in order to "feel in the presence of their partner". This observation comes in competition with the need to announce to the participants that the picture will differ, as it does not encourage them to think of their partner but rather to focus on themselves. As we see, reflections on the method also lead to challenging considerations regarding the JPEs themselves.

Apart from our methodological considerations, a global model is still missing as to whether and how the JPEs participate in the creation of our representations. Many questions are raised by the possibility of brain-to-brain sensitivity: what are the physical phenomena involved? What information is transmitted? How is it used by the brain? The successive observations depict an effect that is both versatile and very sensitive. It is difficult to imagine that such a fundamental matter as the creation of our percept would be dependent on a mechanism so difficult to elicit that it disappears when we are with strangers or when we perceive slightly different stimuli.

In conclusion, the evidence accumulated over the years demonstrate that an effect exists. However, arguing that this effect demonstrates an interaction between two brains at a distance is audacious, as no study yet has shown how a brain's neural activity could physically impact another brain's neural activity and consequently formation of percepts. Therefore, further research should aim not only at characterizing the effect but also at identifying the underlying physical mechanism to pretend to the existence of a brain-to-brain sensitivity.

Contributors

Conceptualization of the research project and of its methodology was done by J. B. Debruille, who also supervised the study and reviewed this thesis. Antoine Bou Khalil, Samuel Calmels and Aidan Schottler-Raymond collected the data from the 40 pairs of participants for this study. Samuel Calmels recruited the participants. The data from Calmels et al. (2023) retreated in this study had been collected by Samuel Calmels, Florence Jarry, Enora Jeuland and Mathieu Lenne. Jean Debruille configured the experimental setup and the stimulus sequences. Antoine Bou Khalil and Samuel Calmels coded the current code for the presentation of the stimuli and processed the data of all participants. Antoine Bou Khalil analysed the data and wrote the manuscript.

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Appendices

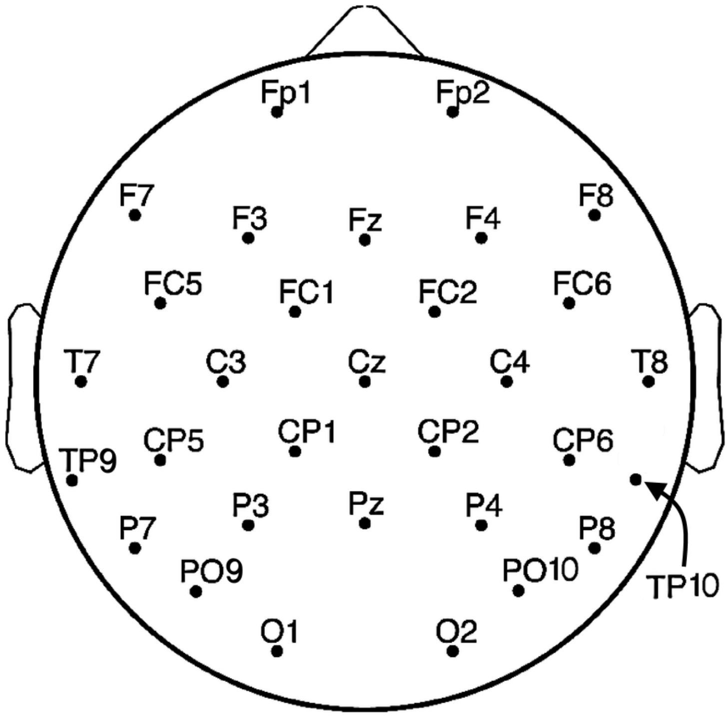

Figure S1 - Scalp locations of the 32 electrodes from which EEG was recorded. (Fcz is not represented because it was not kept in the analyses)

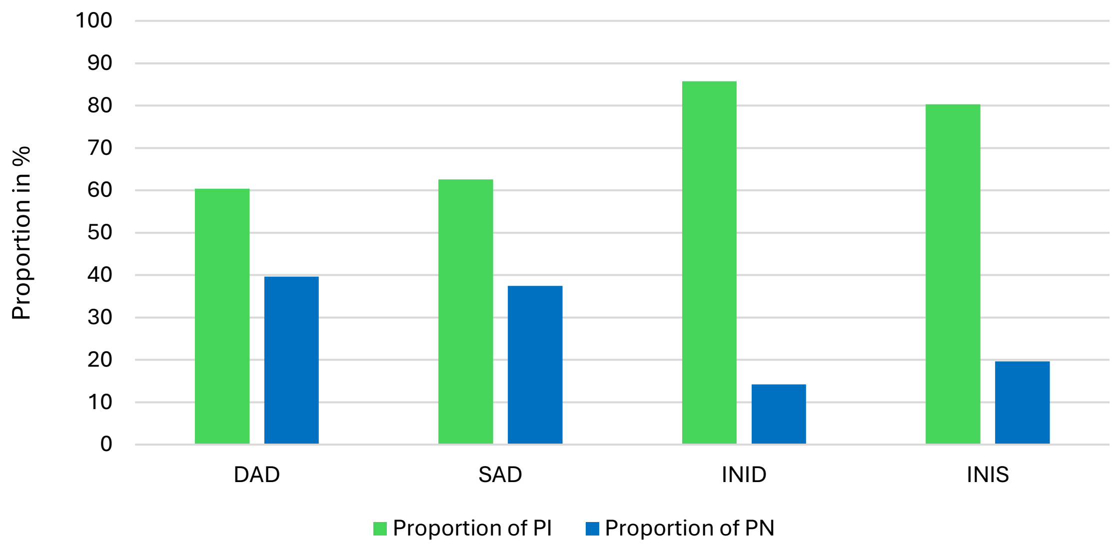

Figure S2 – Proportion of trials that follow a short inter-stimulus-interval (PI trials) or a long ISI (PN trials) amongst the different image-type kind of trials. Due to the pseudo-random order of the stimuli and the greater number of DAD and SAD trials, the comparative proportions of PI and PN trials are very different in the INI trials compared to the main conditions.

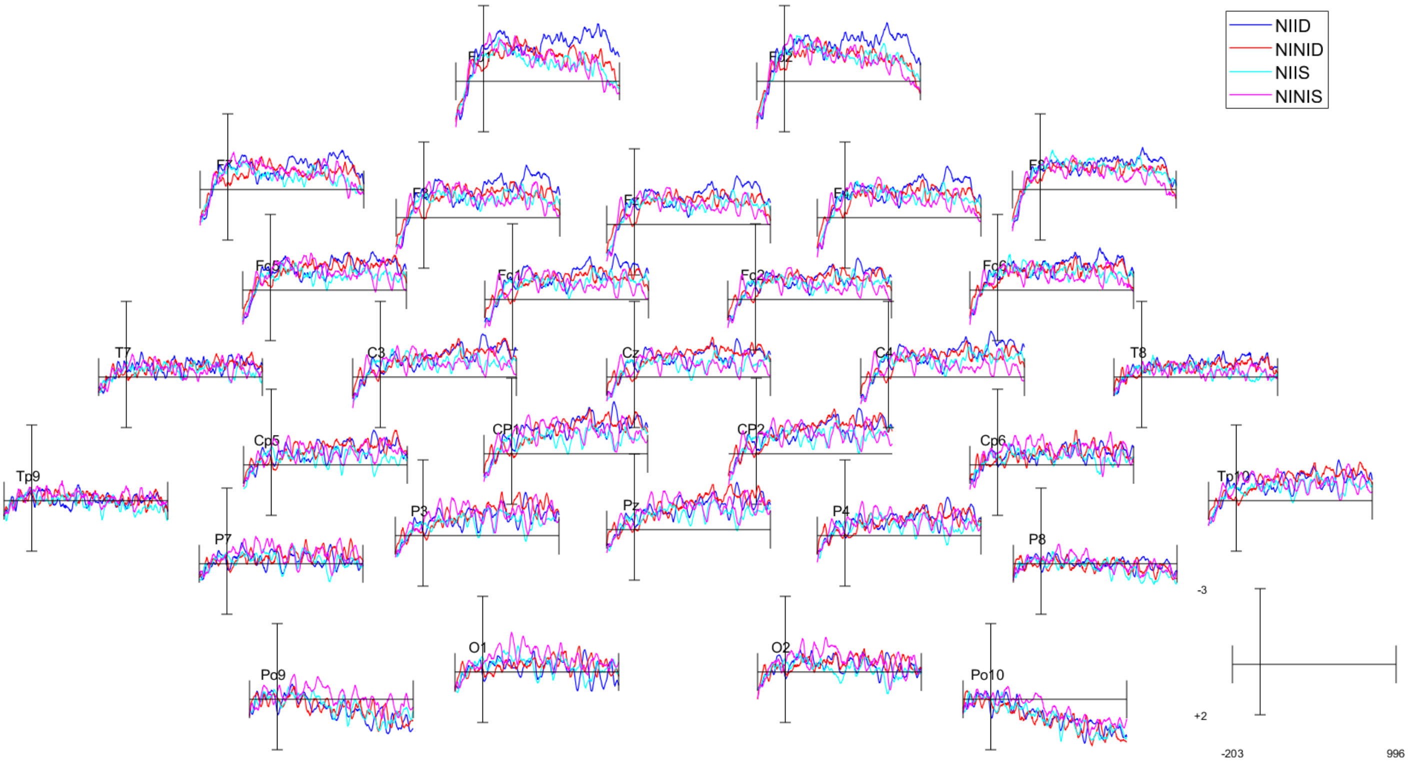

Figure S3 – Grand average ERPs (n=40) of no-image type of trials conditions separated by block. Voltage is represented on the y-axis (microvolts), the x-axis represents time from stimulus onset in milliseconds.

Participant	DAD (140)	SAD (140)	INI (70)
1H1	98	69	47
1H2	67	116	49
2H1	102	85	54
2H2	133	128	63
3H1	31	72	24
3H2	79	77	36
4H1	78	92	48
4H2	117	75	46
5H1	86	123	47
5H2	111	110	52
6H1	134	117	63
6H2	131	128	65
7H1	120	115	59
7H2	128	128	64
8H1	117	131	63
8H2	105	120	57
9H1	118	131	63
9H2	99	110	52
10H1	120	123	59
10H2	110	109	61
11H1	124	113	54
11H2	115	118	54
12H1	121	119	53
12H2	125	130	67
13H1	95	122	50
13H2	126	115	64
14H1	128	134	66
14H2	110	100	50
15H1	108	115	60
15H2	99	105	53
16H1	121	111	60
16H2	133	116	60
17H1	94	102	45
17H2	123	102	56
18H1	117	117	59
18H2	133	134	67
19H1	113	108	58
19H2	107	131	64
20H1	104	110	56
20H2	121	96	61

Participant	DAD (140)	SAD (140)	INI (70)
Mean	110.025	111.425	55.725
SD	20.6080486	17.2387273	8.75884169
FA	111.5	116.5	56.2
	19.8284308	8.733715	6.47731083
FT	109.533333	109.733333	55.5666667
	21.1688342	19.082278	9.48931644
H1	106.45	110.45	54.4
	22.9724664	18.2337888	9.4110797
H2	113.6	112.4	57.05
	17.8071541	16.5986683	8.07514054

Table S1 – Number of accepted trials for all three image-type conditions for each participant. Numeration corresponds to the pair number, H1/H2 to the individual designations.

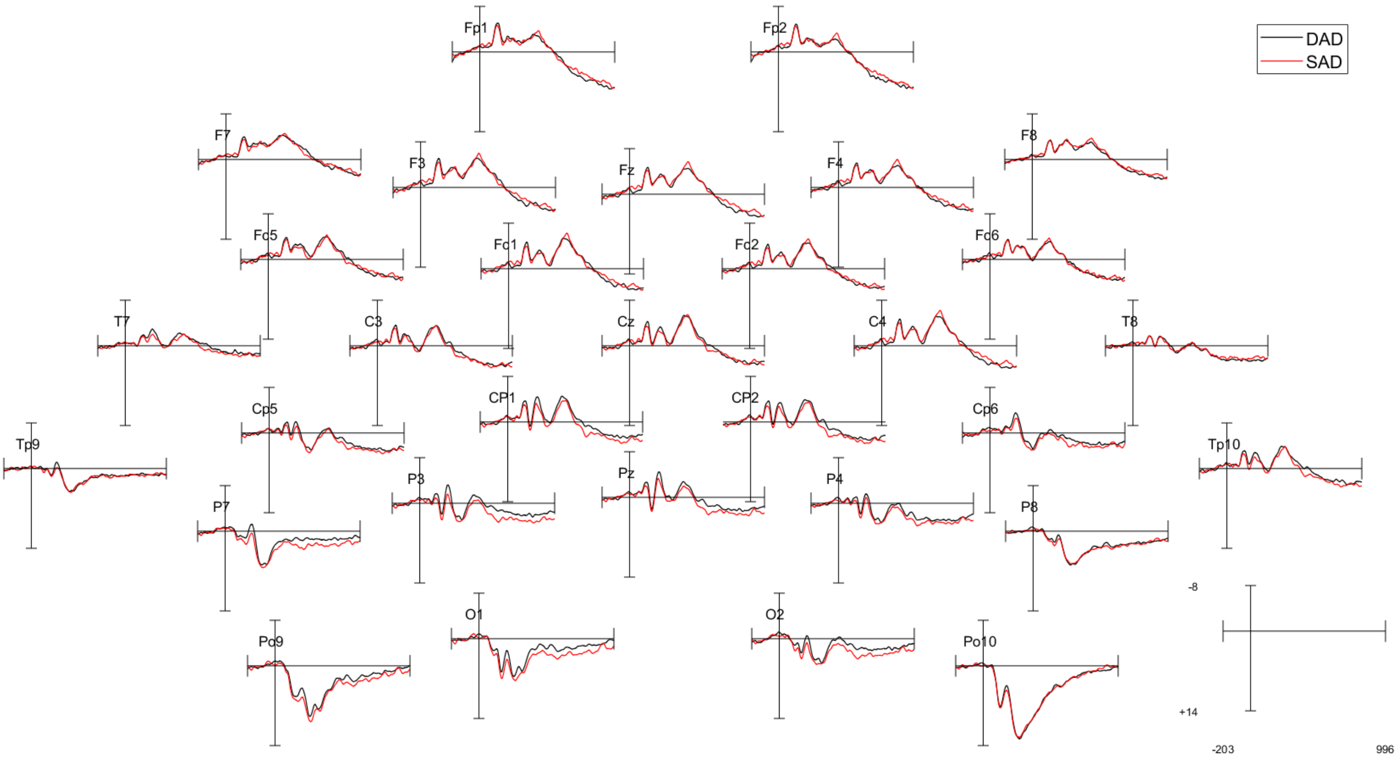

Figure S4 – Grand average ERPs of the Felt-Alone group (n=10) for the main conditions. Voltage is represented on the y-axis (microvolts), the x-axis represents time from stimulus onset in milliseconds.

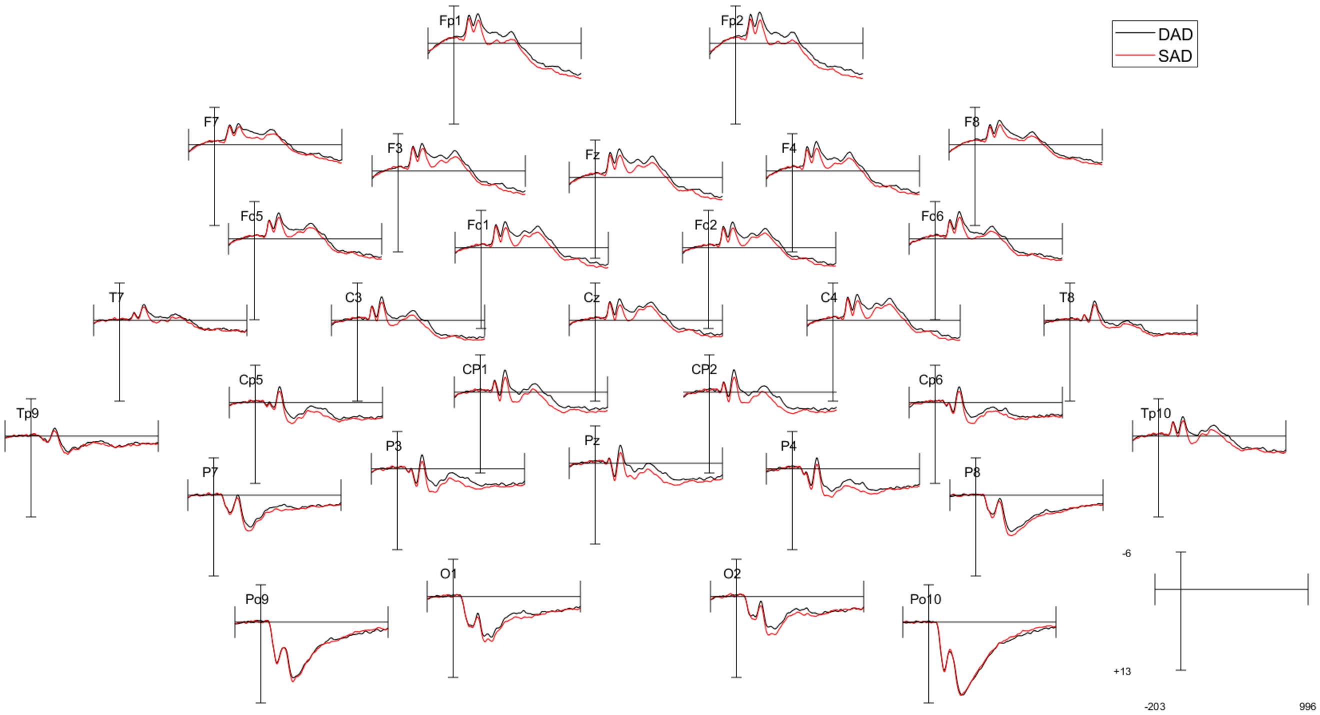

Figure S5 – Grand average ERPs of the Felt-Together group (n=30) for the main conditions. Voltage is represented on the y-axis (microvolts), the x-axis represents time from stimulus onset in milliseconds.

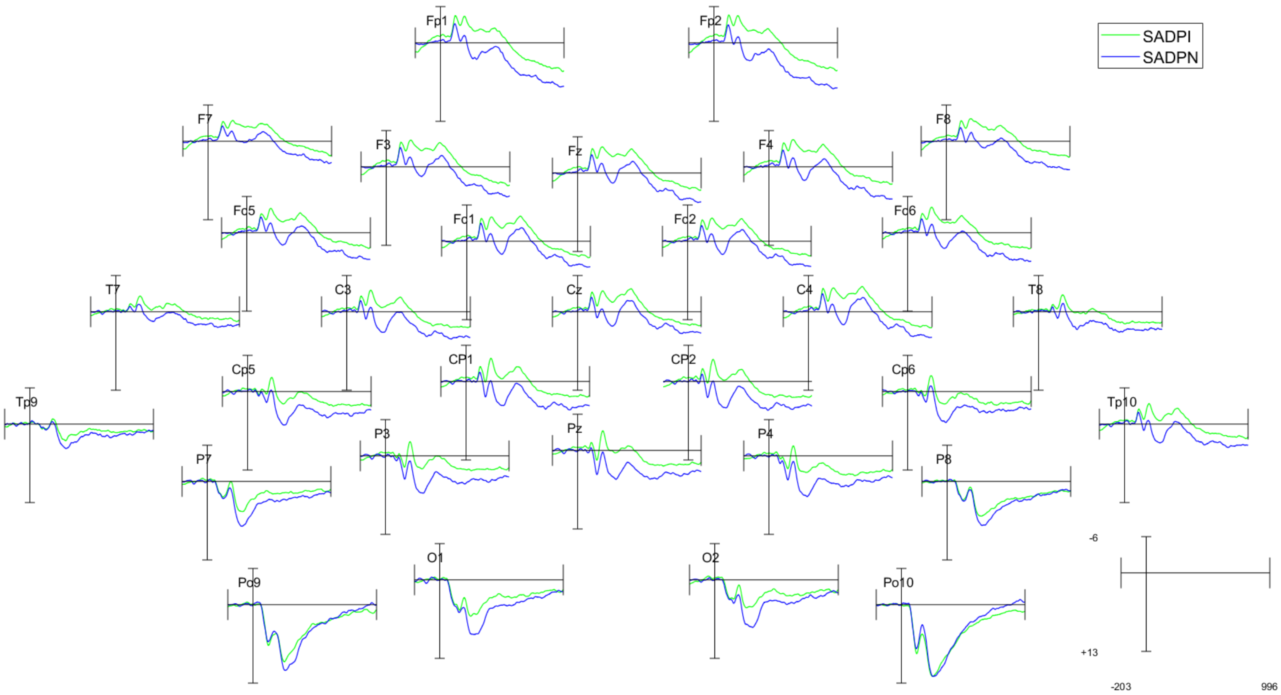

Figure S6 – Grand average ERPs (n=40) for the SAD trials separated between Post-Image (PI) and Post-No Image (PN) trials. Voltage is represented on the y-axis (microvolts), the x-axis represents time from stimulus onset in milliseconds.

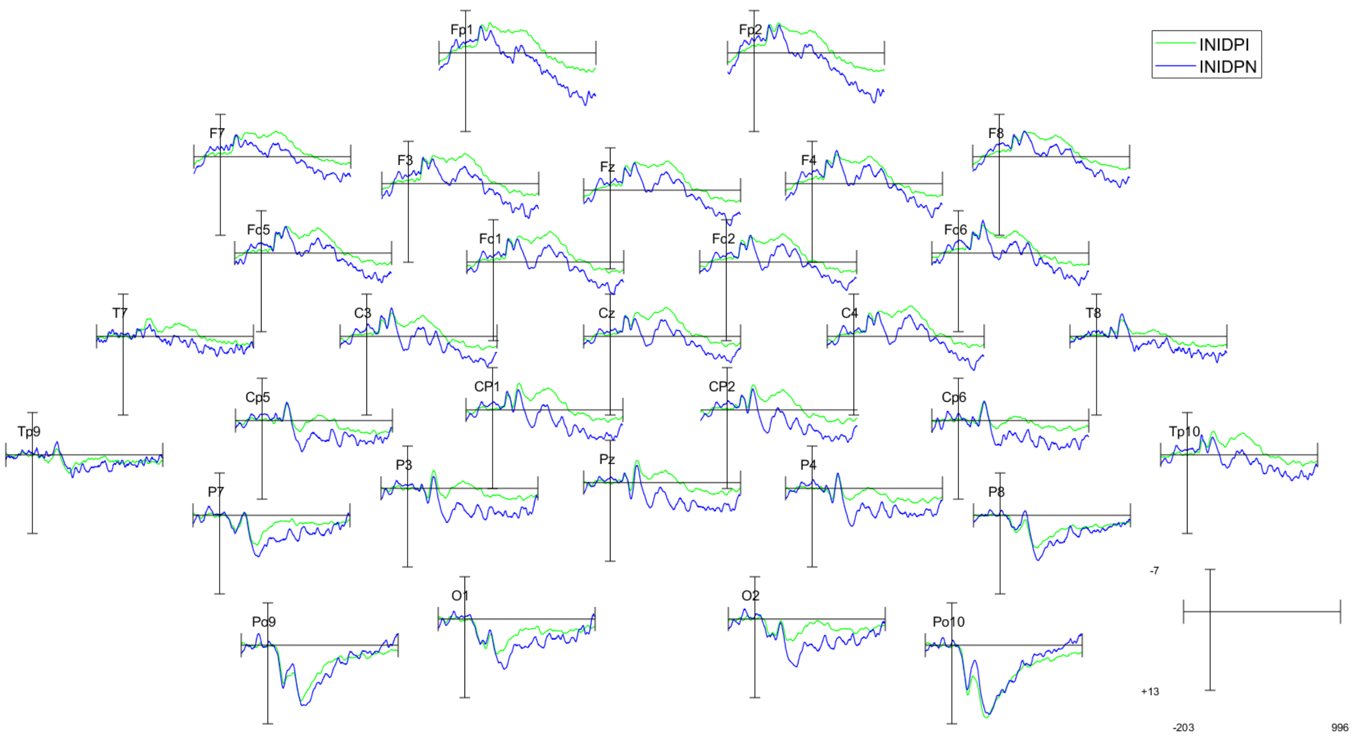

Figure S7 – Grand average ERPs (n=40) for the INID trials separated between Post-Image (PI) and Post-No Image (PN) trials. Voltage is represented on the y-axis (microvolts), the x-axis represents time from stimulus onset in milliseconds.

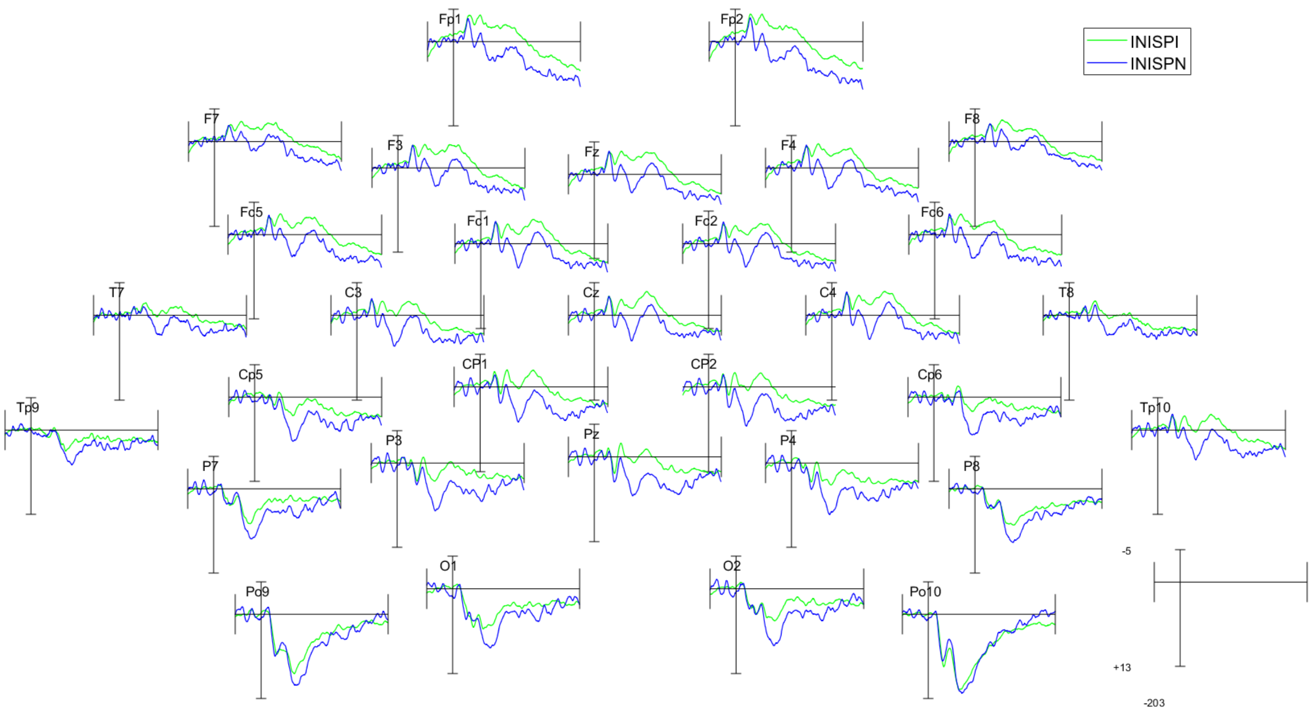

Figure S8 – Grand average ERPs (n=40) for the INID trials separated between Post-Image (PI) and Post-No Image (PN) trials. Voltage is represented on the y-axis (microvolts), the x-axis represents time from stimulus onset in milliseconds.

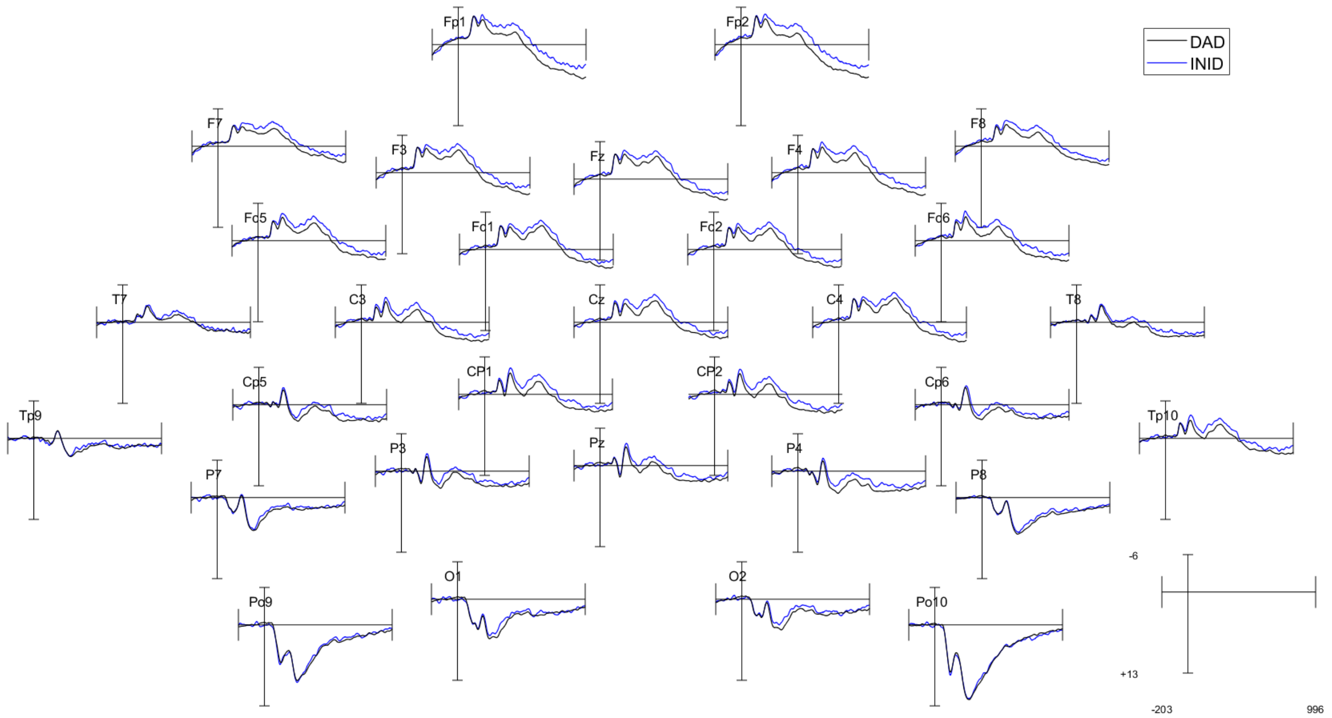

Figure S9 – Grand average ERPs (n=40) of the INID and DAD trials before separation. Voltage is represented on the y-axis (microvolts), the x-axis represents time from stimulus onset in milliseconds.

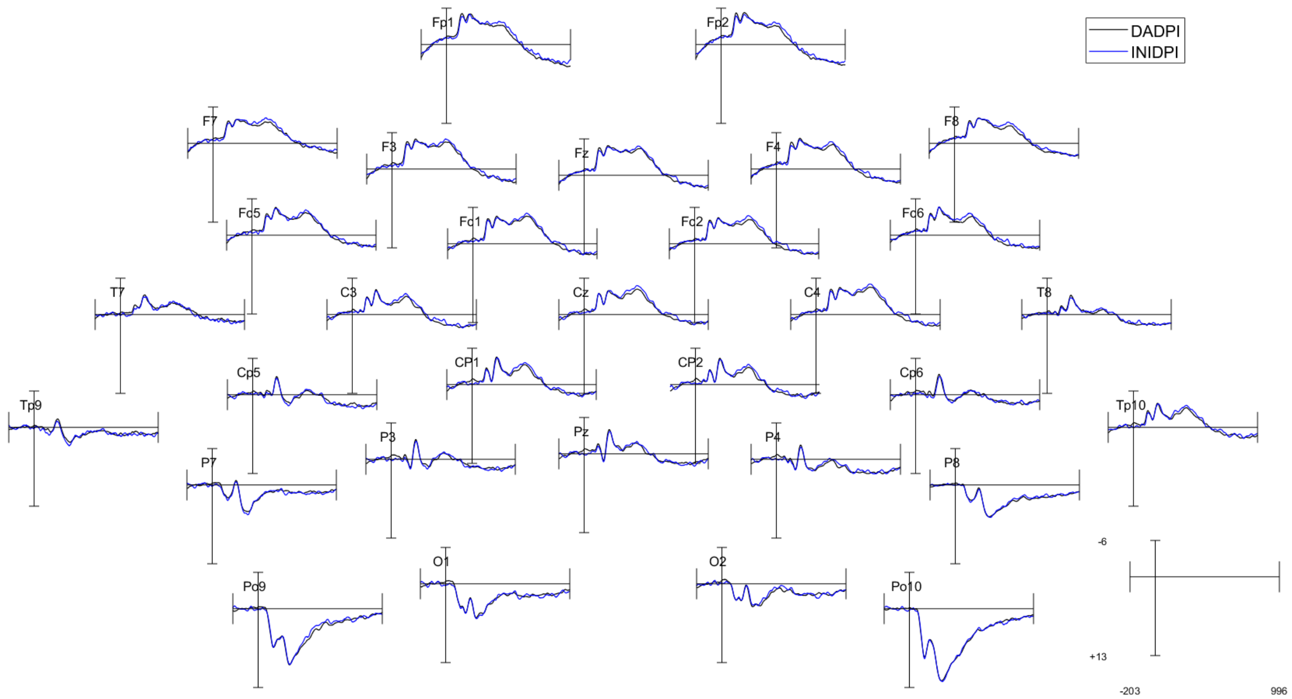

Figure S10 – Grand average ERPs (n=40) for the INID and DAD trials, Post-Image (PI) only. Voltage is represented on the y-axis (microvolts), the x-axis represents time from stimulus onset in milliseconds.

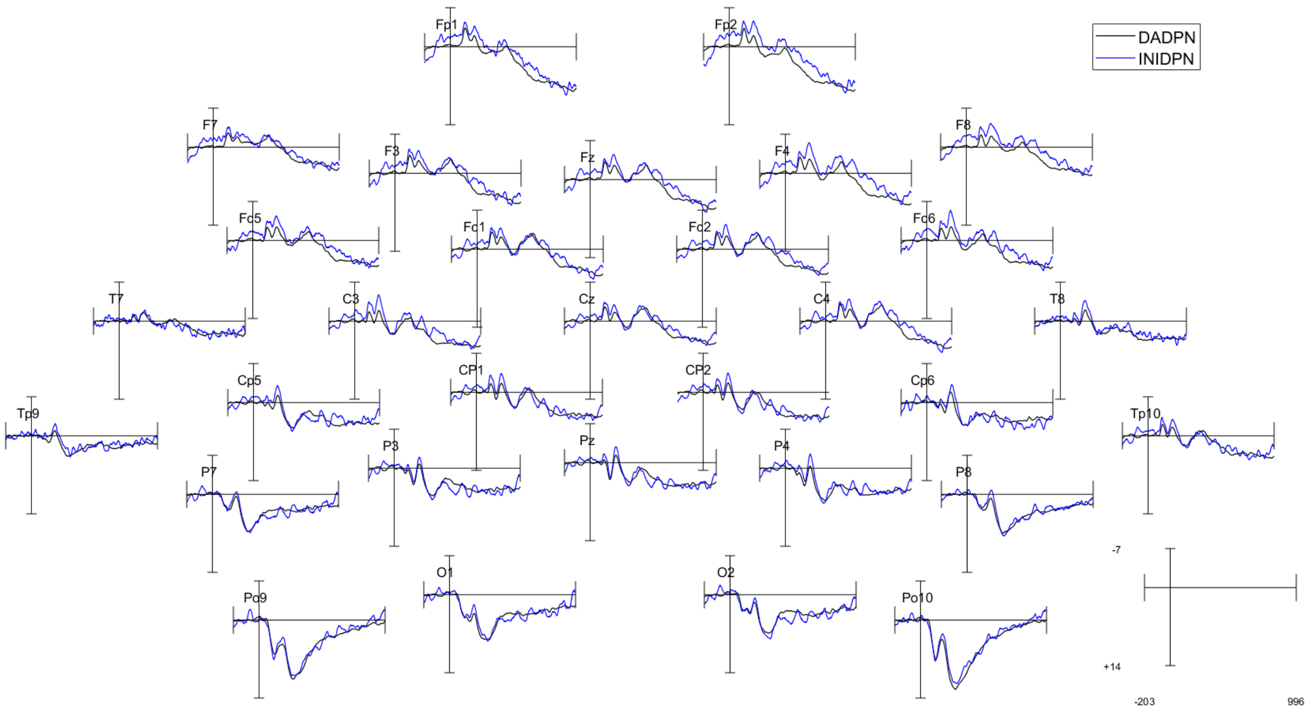

Figure S11 – Grand average ERPs (n=40) for the INID and DAD trials, Post-No Image (PN) only. Voltage is represented on the y-axis (microvolts), the x-axis represents time from stimulus onset in milliseconds.

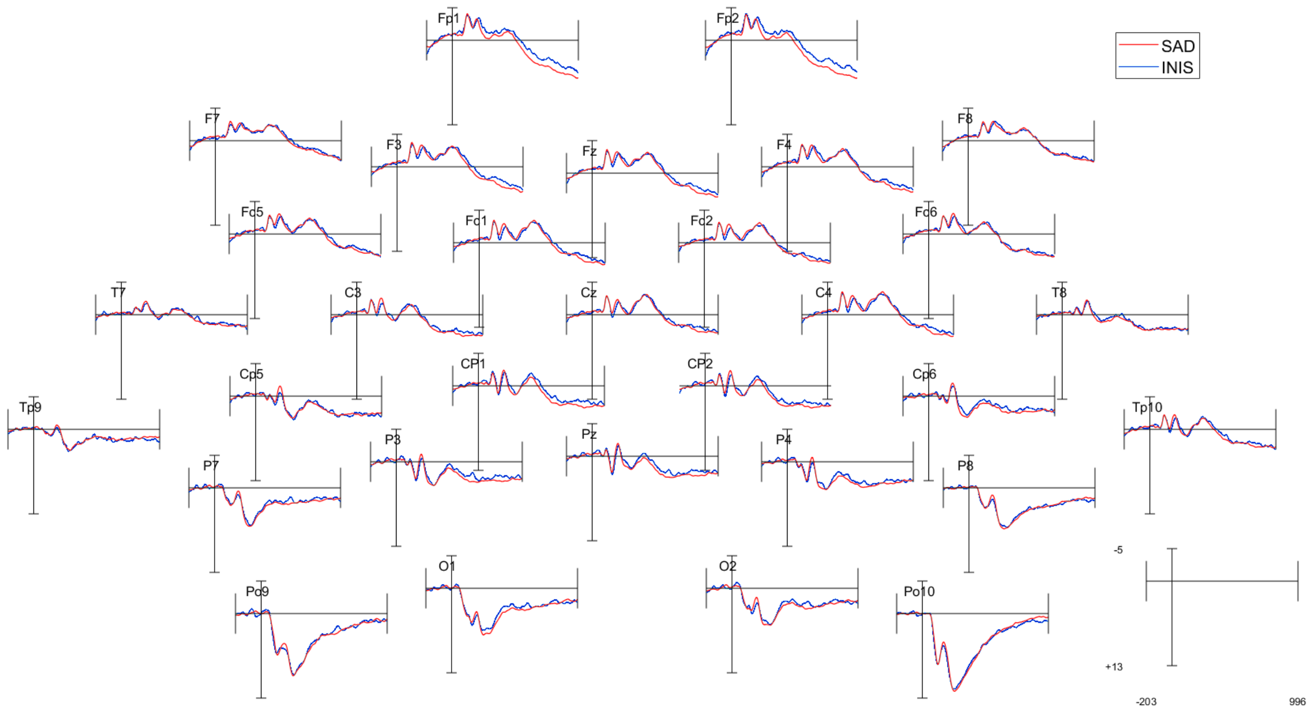

Figure S12 – Grand average ERPs (n=40) for the INIS and SAD trials before separation. Voltage is represented on the y-axis (microvolts), the x-axis represents time from stimulus onset in milliseconds.

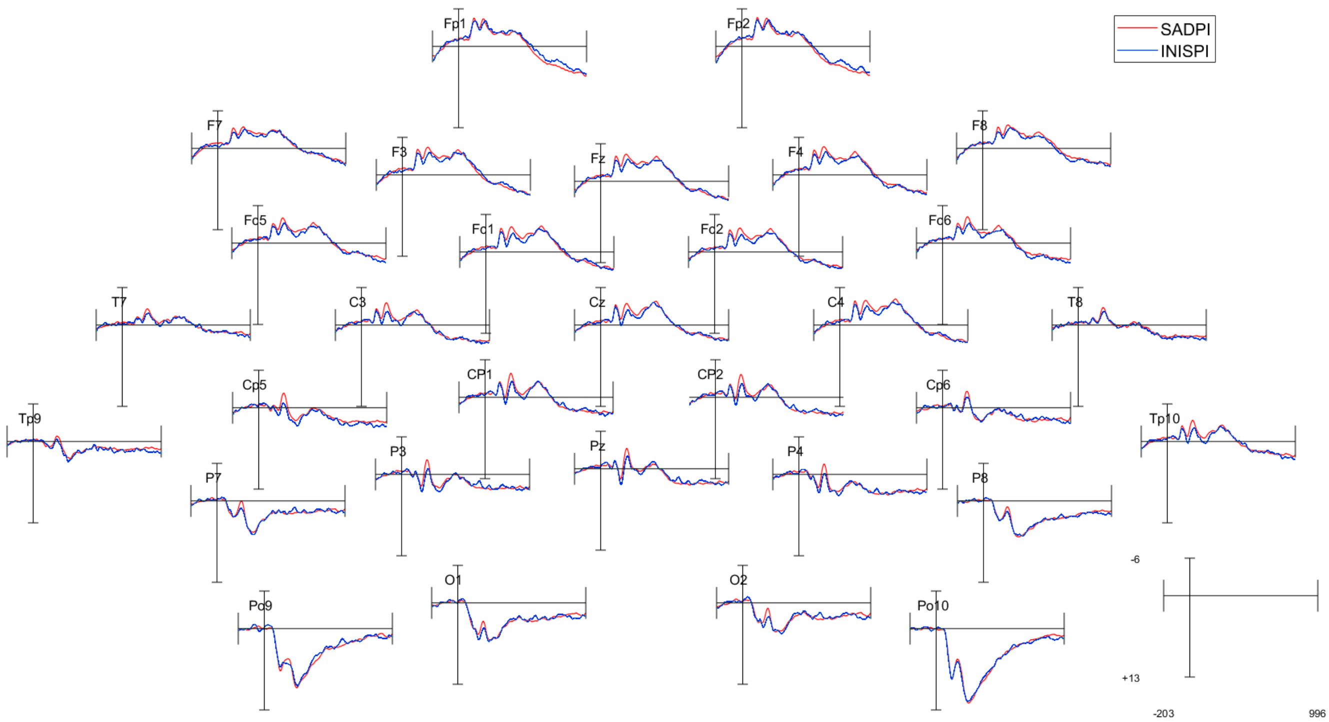

Figure S13 – Grand average ERPs (n=40) for the INIS and SAD trials, Post-Image (PI) only. Voltage is represented on the y-axis (microvolts), the x-axis represents time from stimulus onset in milliseconds

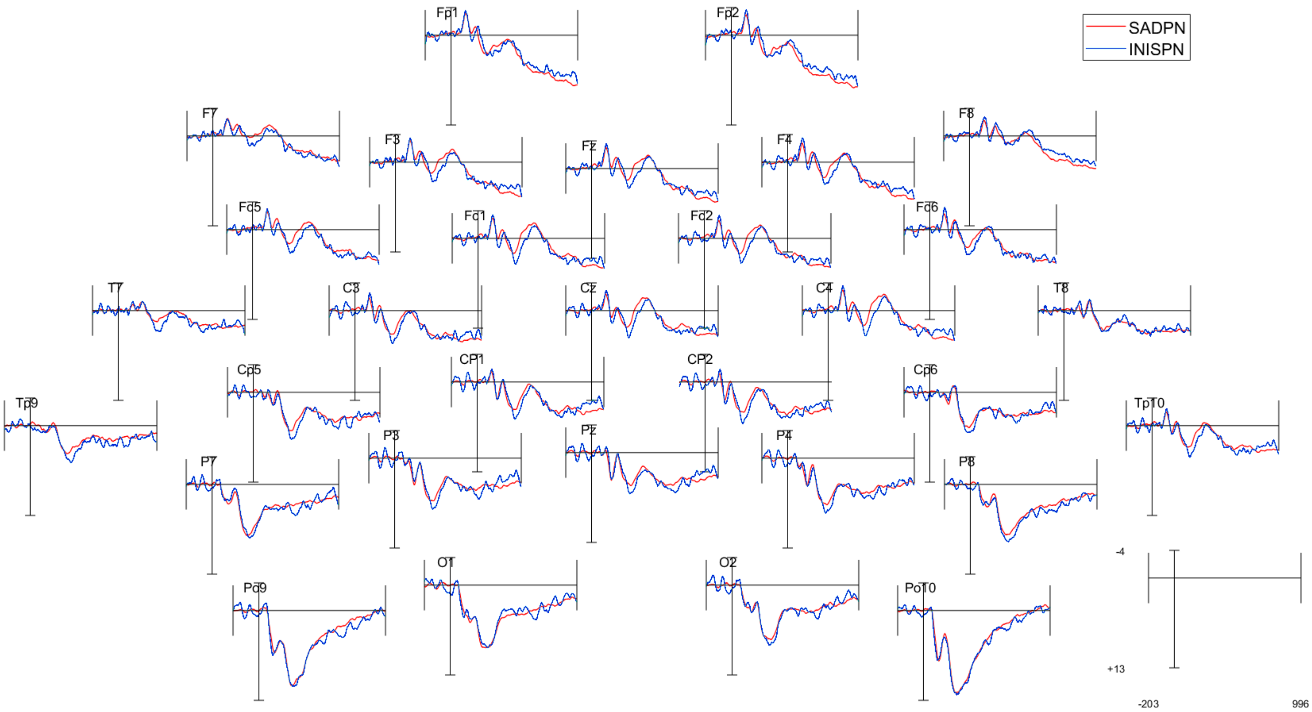

Figure S14 – Grand average ERPs (n=40) for the INIS and SAD trials, Post-No Image (PN) only. Voltage is represented on the y-axis (microvolts), the x-axis represents time from stimulus onset in milliseconds.

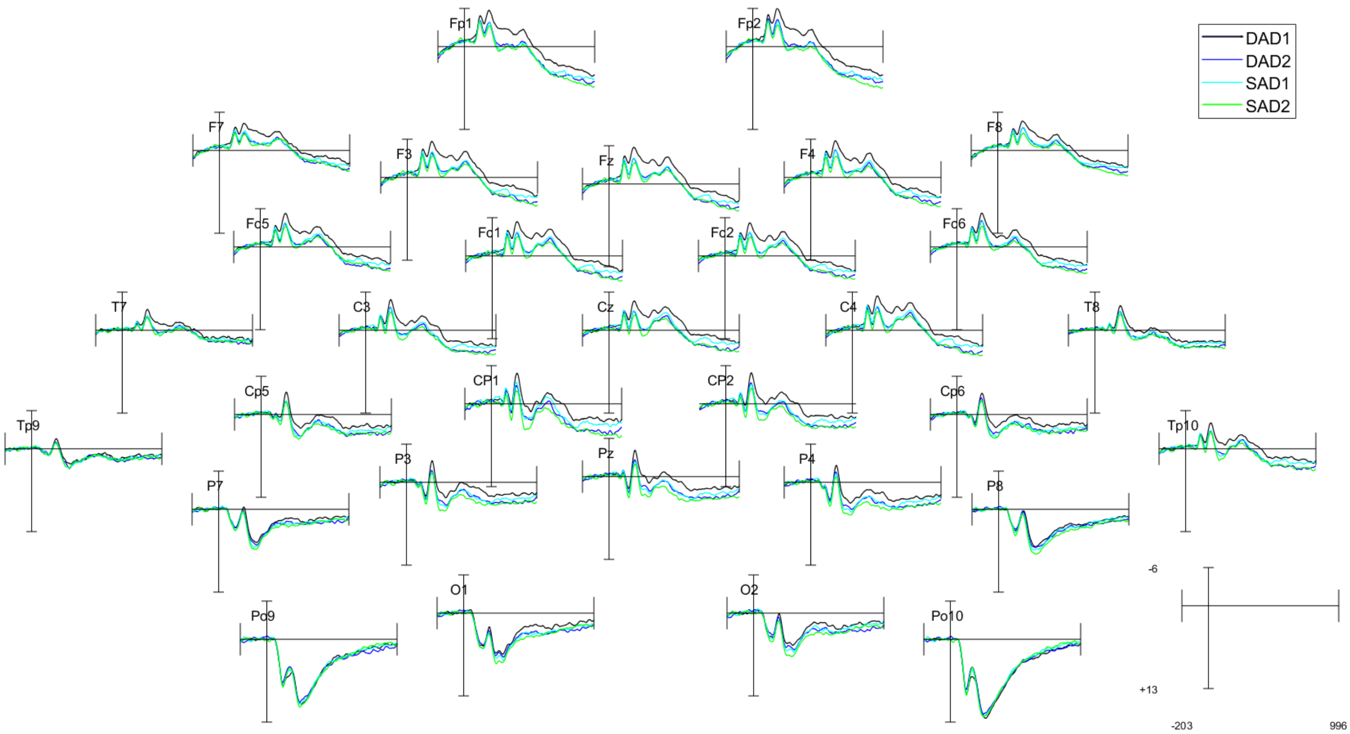

Figure S15 – Grand average ERPs of the four successive parts, Felt-Together group (n=30). Voltage is represented on the y-axis (microvolts), the x-axis represents time from stimulus onset in milliseconds.

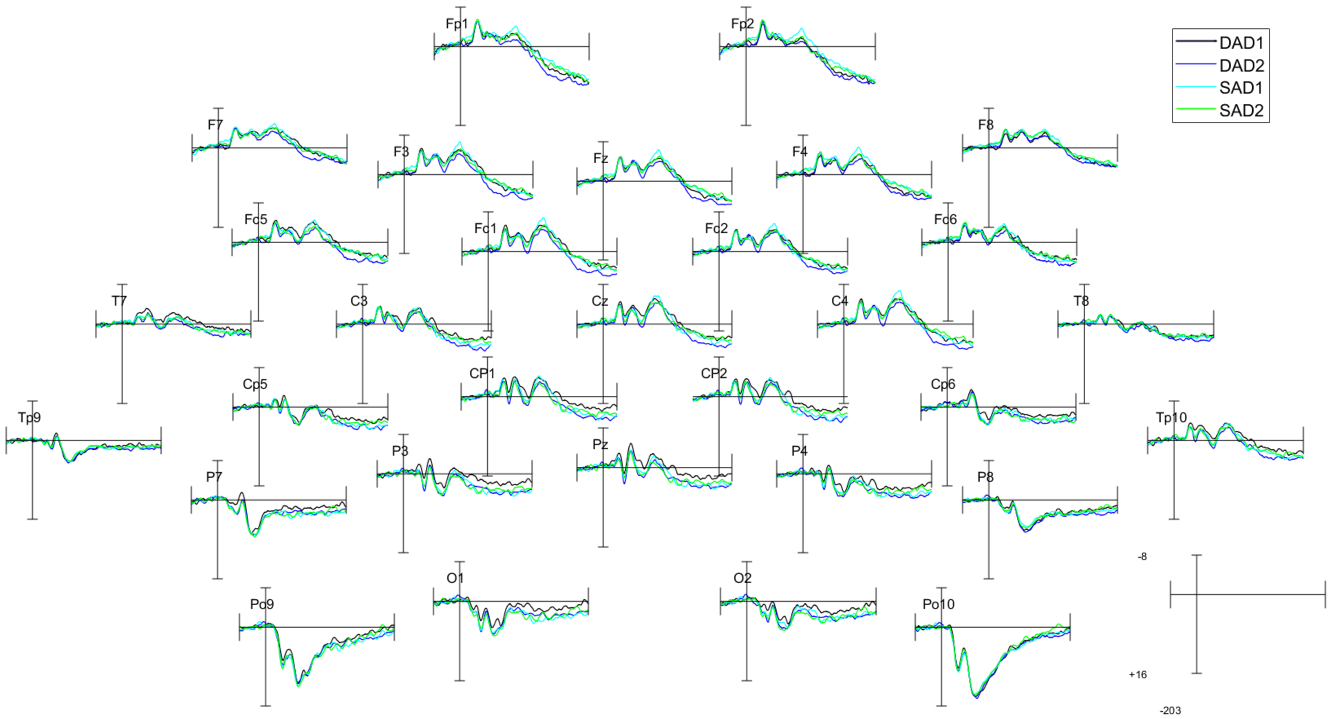

Figure S16 – Grand average ERPs of the four successive parts, Felt-Alone group (n=10). Voltage is represented on the y-axis (microvolts), the x-axis represents time from stimulus onset in milliseconds.

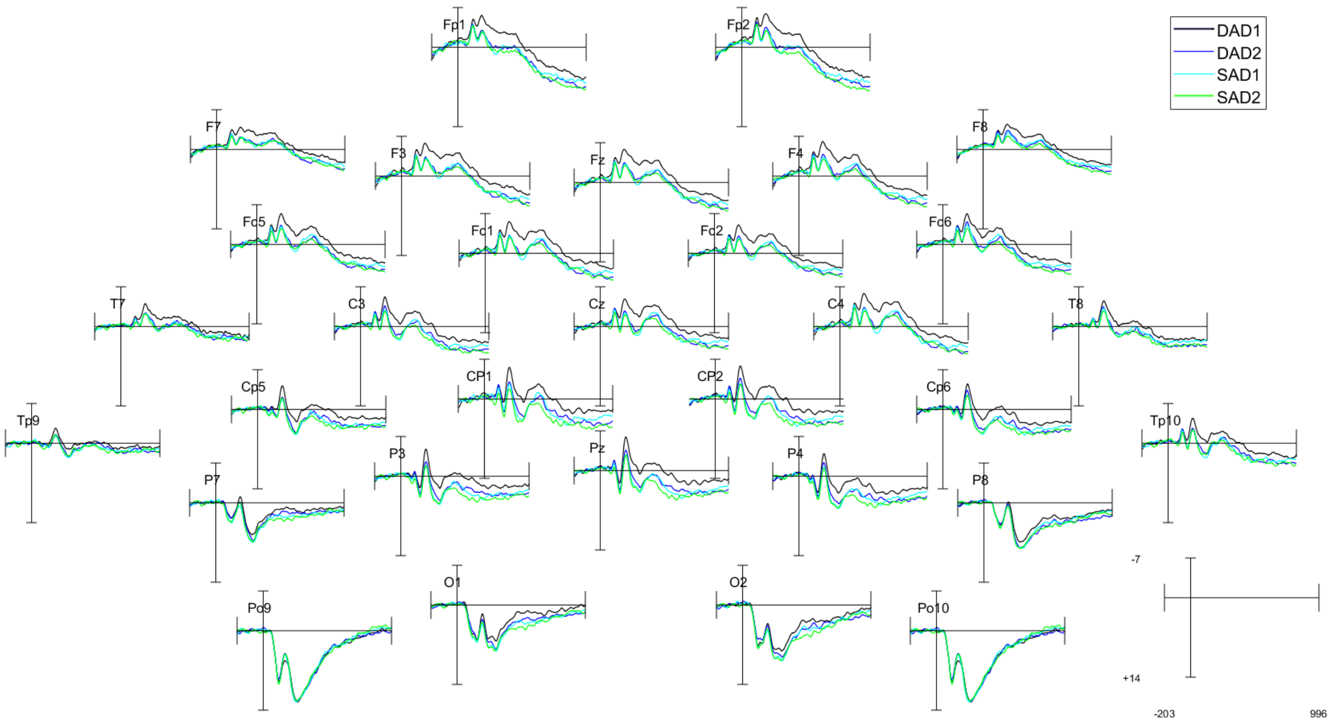

Figure S17 – Grand average ERPs of the four successive parts, H1 participants (n=20). Voltage is represented on the y-axis (microvolts), the x-axis represents time from stimulus onset in milliseconds.

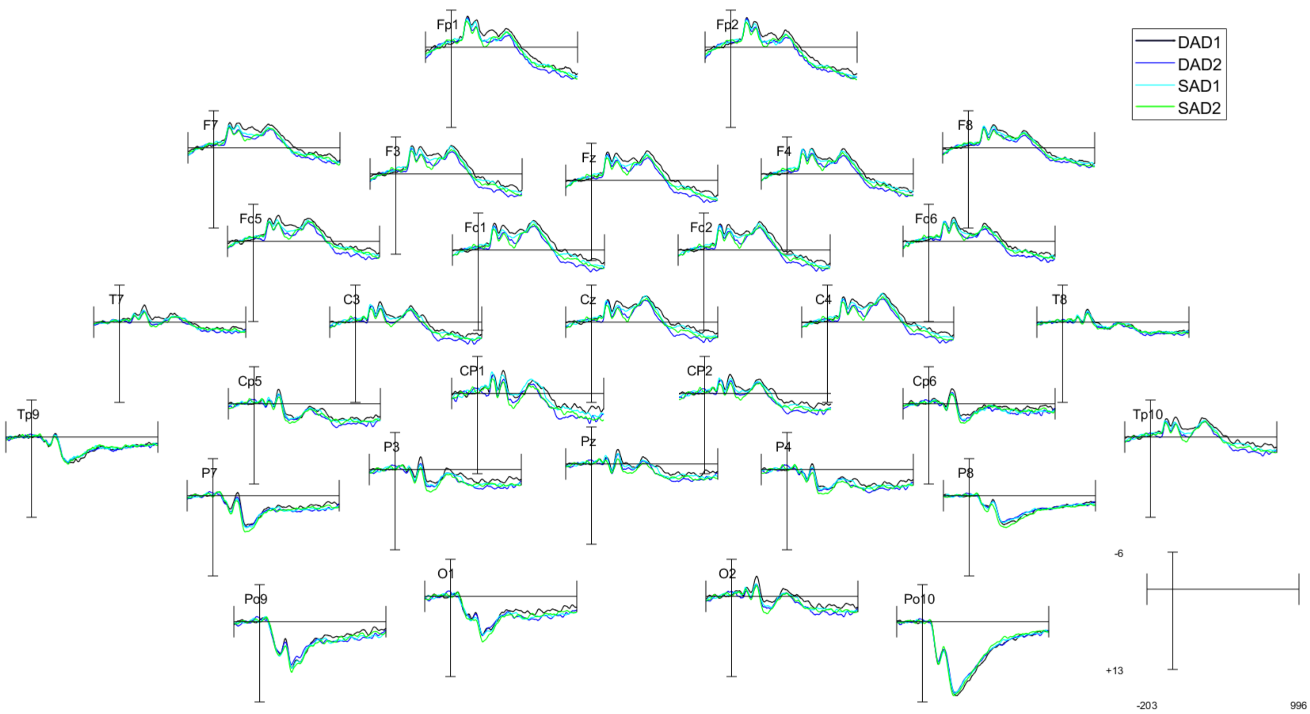

Figure S18 – Grand average ERPs of the four successive parts, H2 participants (n=20). Voltage is represented on the y-axis (microvolts), the x-axis represents time from stimulus onset in milliseconds.

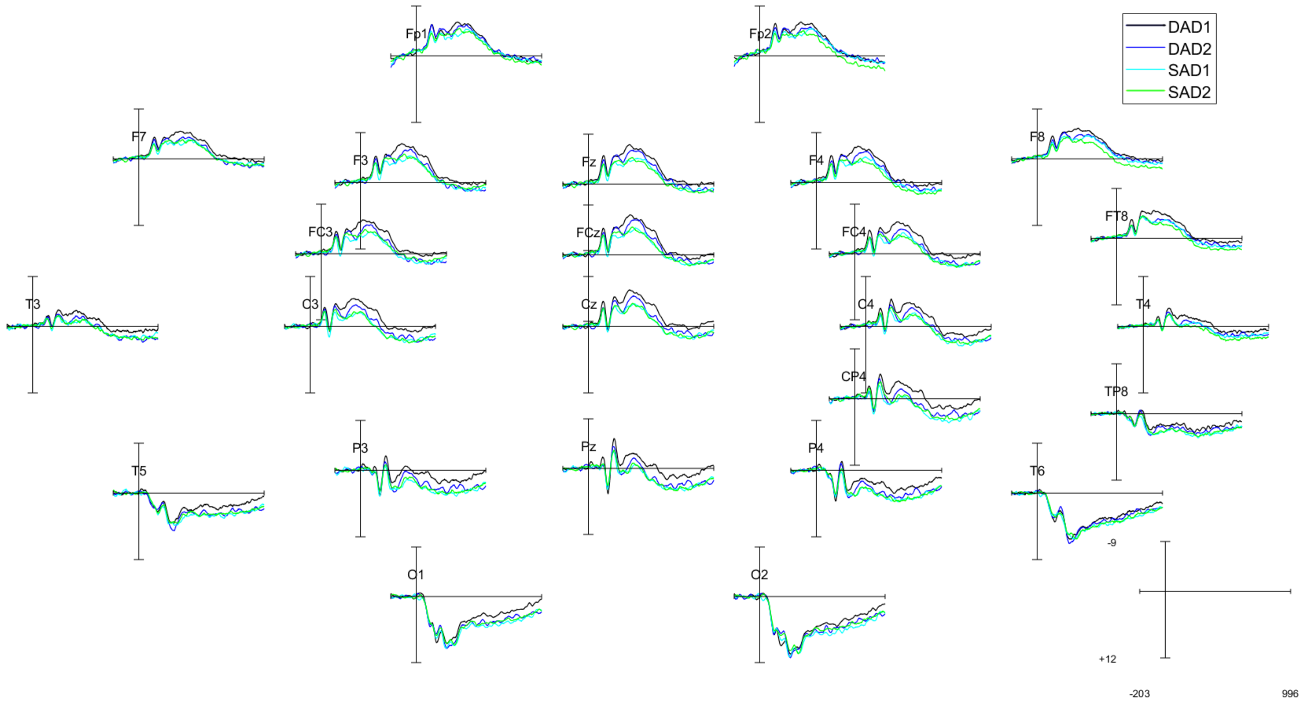

Figure S19 – Grand average ERPs of the four successive parts, Felt-Together group (n=24), Calmels et al.'s data. Voltage is represented on the y-axis (microvolts), the x-axis represents time from stimulus onset in milliseconds.

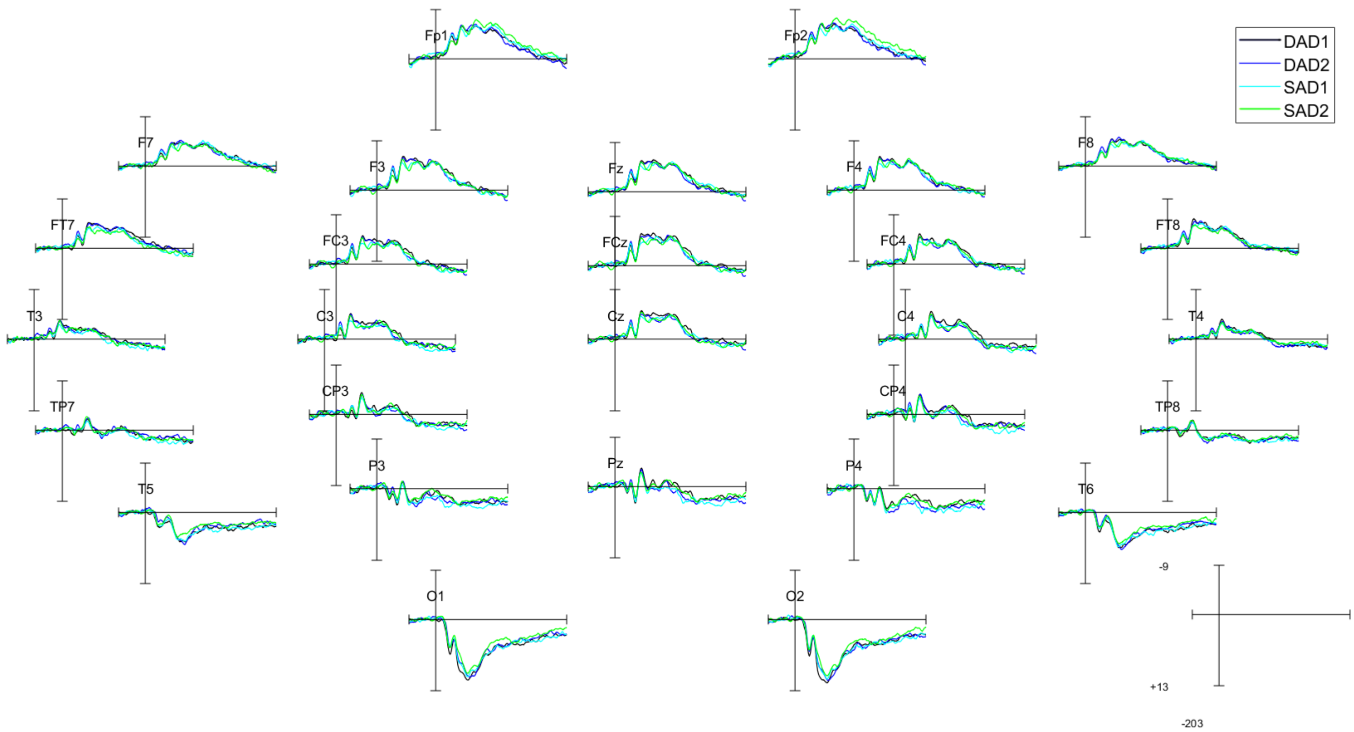

Figure S20 – Grand average ERPs of the four successive parts, Felt-Alone group (n=24), Calmels et al.'s data. Voltage is represented on the y-axis (microvolts), the x-axis represents time from stimulus onset in milliseconds.

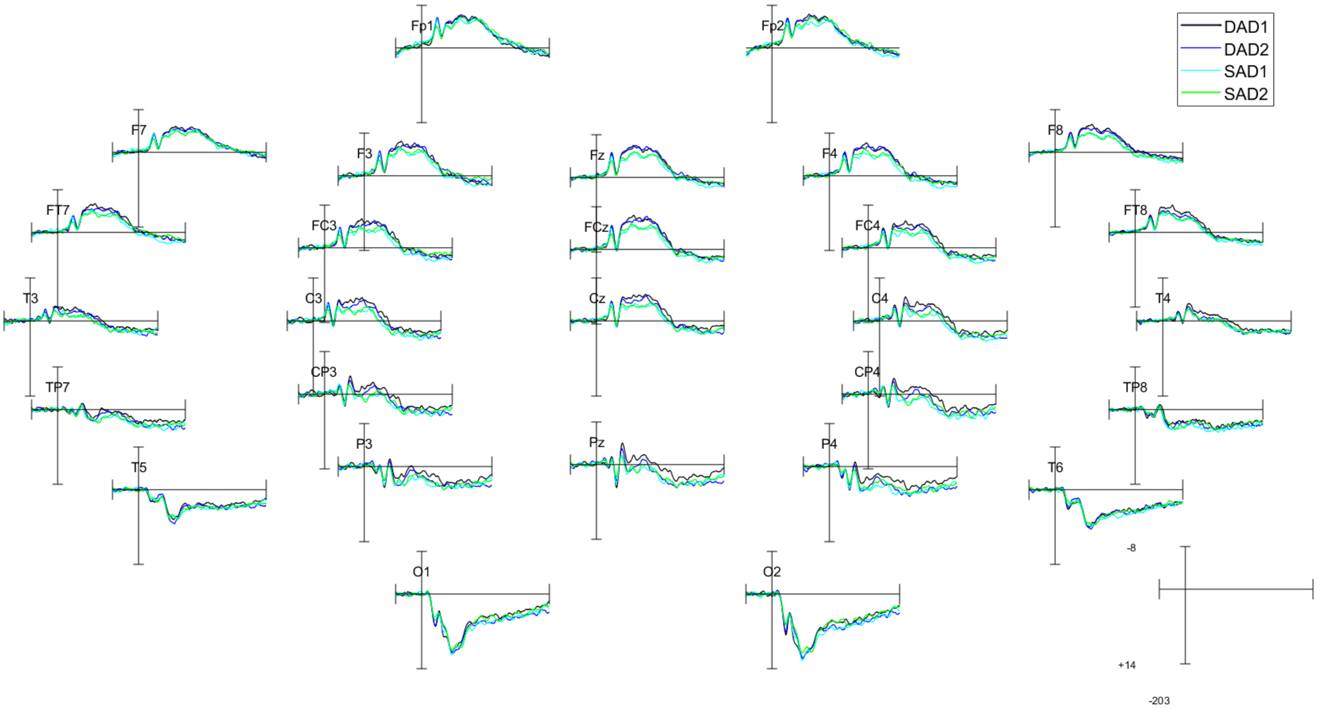

Figure S21 – Grand average ERPs of the four successive parts, H1 participants (n=24), Calmels et al.'s data. Voltage is represented on the y-axis (microvolts), the x-axis represents time from stimulus onset in milliseconds.

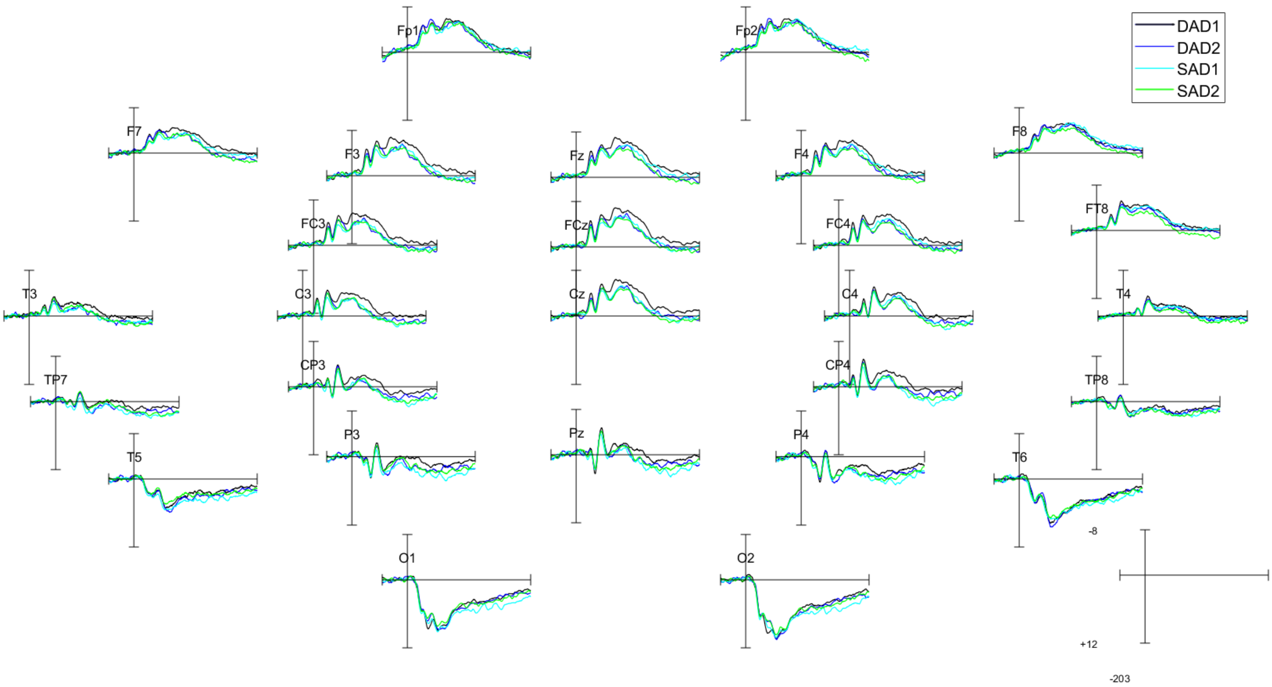

Figure S22 – Grand average ERPs of the four successive parts, H2 participants (n=24), Calmels et al.'s data. Voltage is represented on the y-axis (microvolts), the x-axis represents time from stimulus onset in milliseconds.

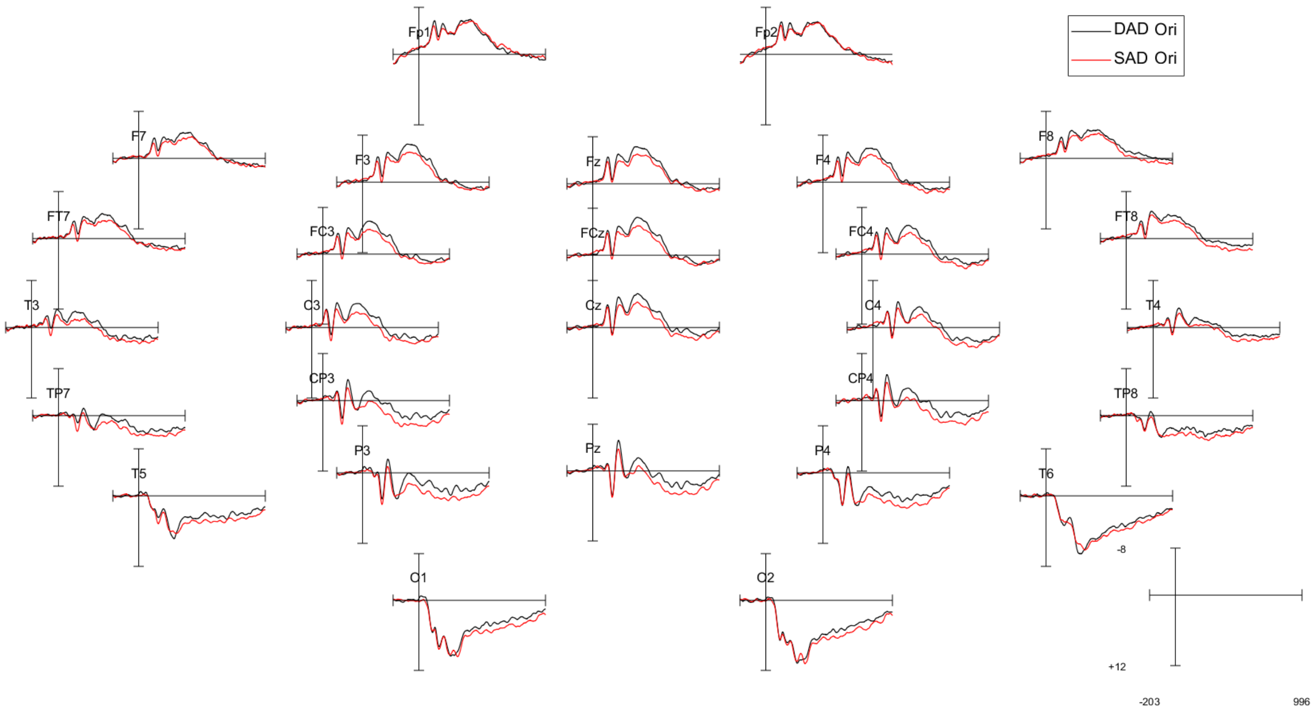

Figure S23 – Grand average ERPs of the two main conditions, DAD-first/Felt-together subgroup, original pool of participants only (n=16), Calmels et al.'s data. Y-axis : voltage in microvolts. X-axis : time from stim. onset, ms.

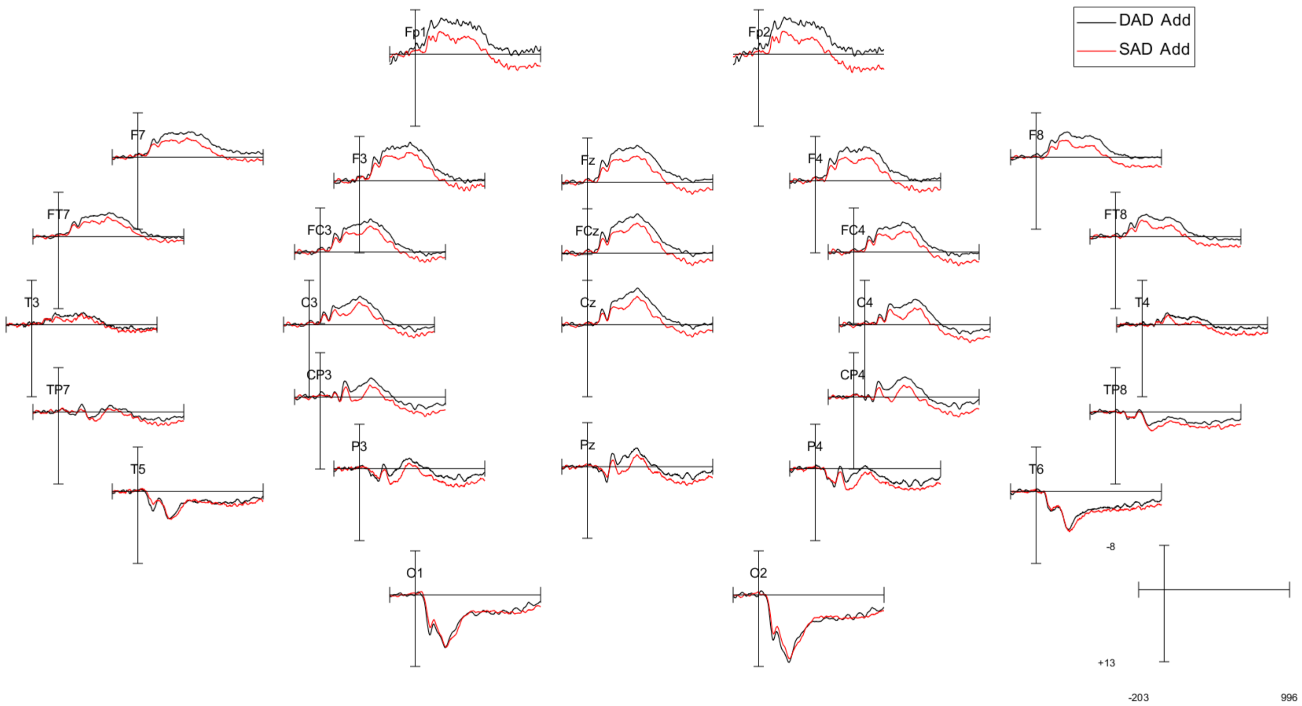

Figure S24 – Grand average ERPs of the two main conditions, DAD-first/Felt-together subgroup, additional pool of participants only (n=12), Calmels et al.'s data. Y-axis : voltage in microvolts. X-axis : time from stim. onset, ms.

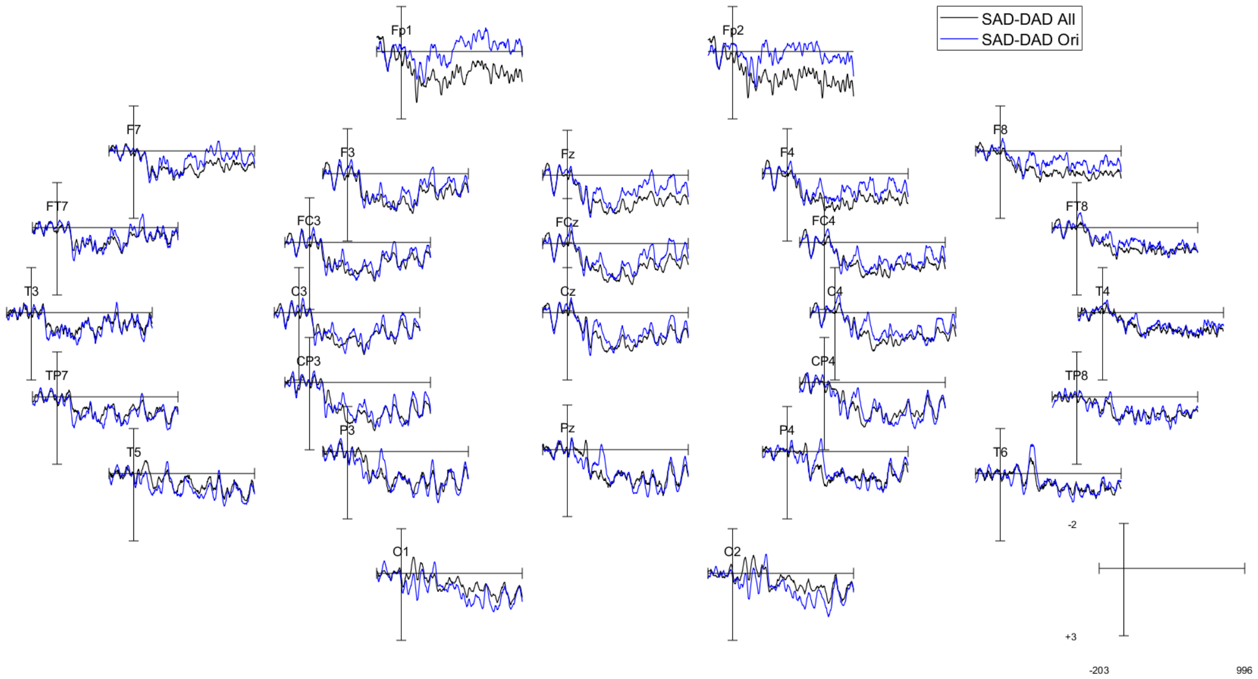

Figure S25 – Grand average ERPs subtracted of the two main conditions (SAD minus DAD), before (Ori, n=16) and after inclusion of the additional participants (All, n=28), Calmels et al.'s data. Y-axis : voltage in microvolts. X-axis : time from stim. onset, ms.

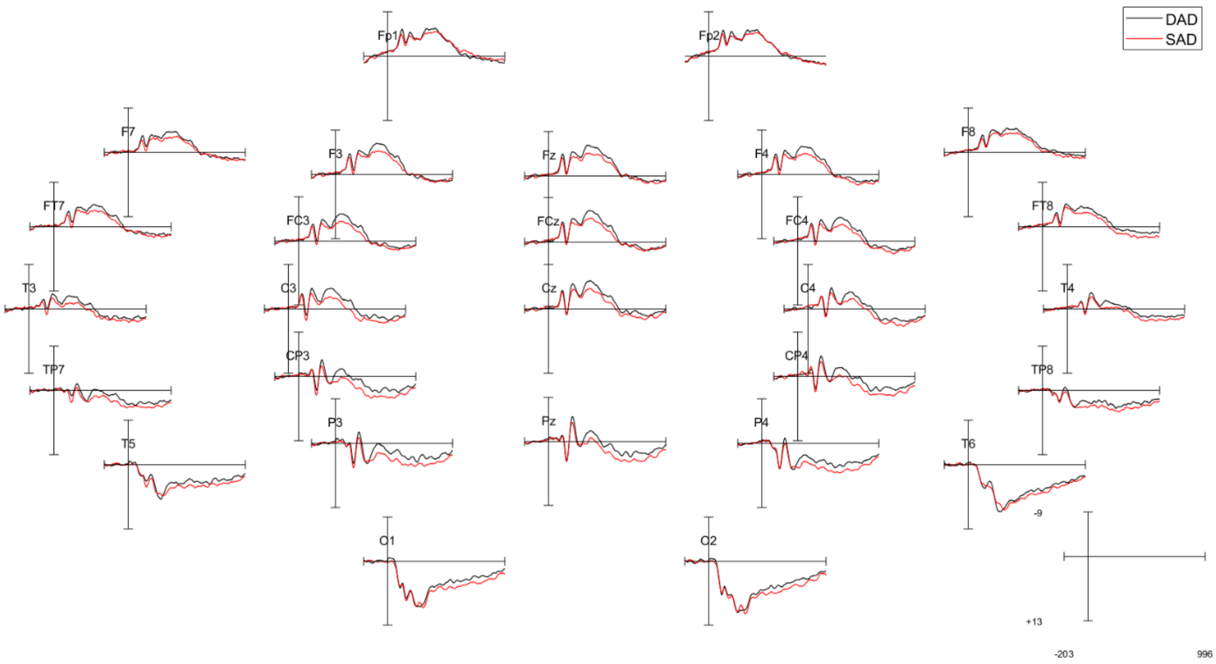

Figure S26 – Grand average ERPs of the two main conditions, DAD-first/Felt-together subgroup, original pool of participants only (n=14), Calmels et al.’s data. Y-axis : voltage in microvolts. X-axis : time from stim. onset, ms.

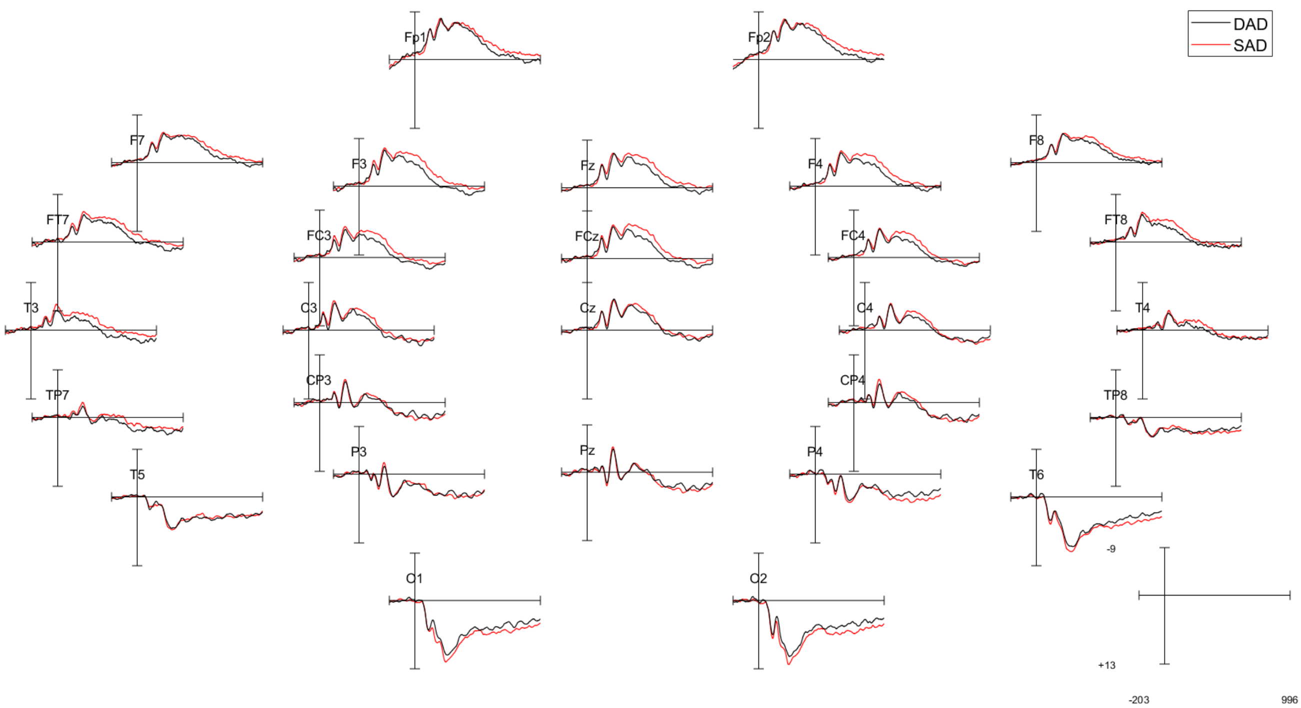

Figure S27 – Grand average ERPs of the two main conditions, SAD-first/Felt-together subgroup, original pool of participants only (n=14), Calmels et al.’s data. Y-axis : voltage in microvolts. X-axis : time from stim. onset, ms.

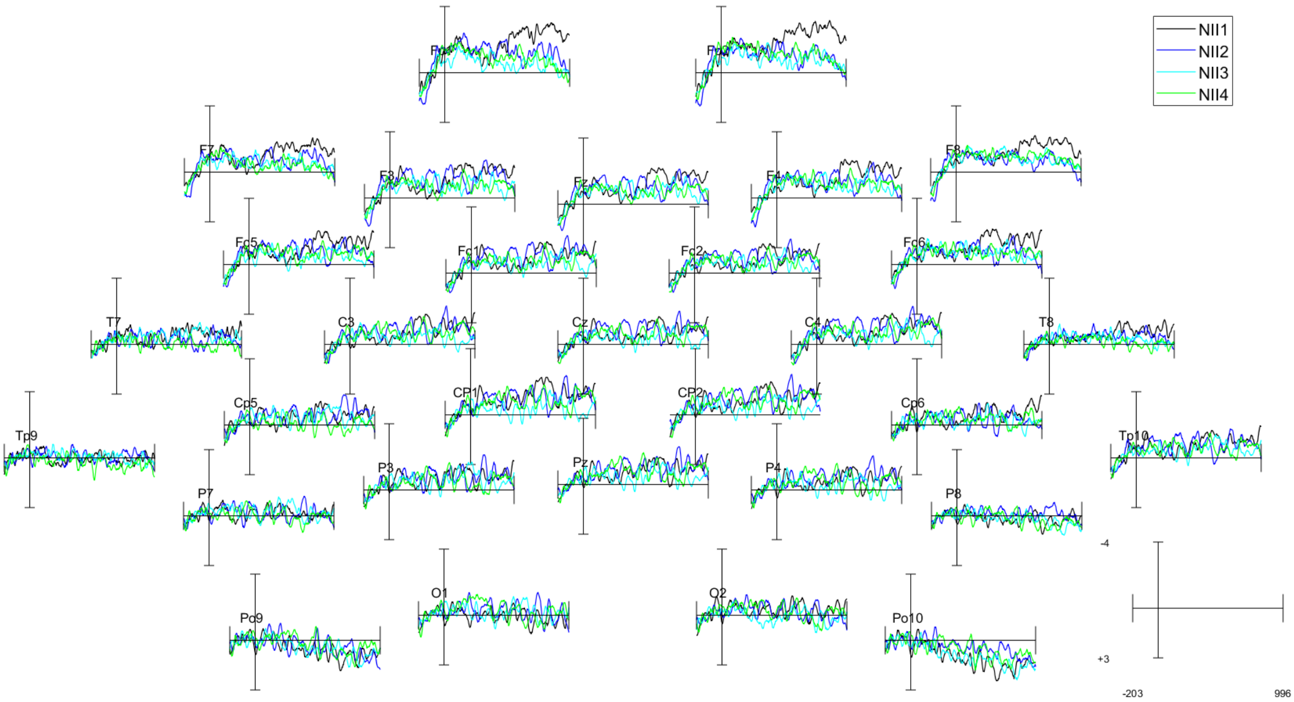

Figure S28 – Grand average ERPs (n=40) of the of the four successive parts, No-Image-Image (NII) trials. Voltage is represented on the y-axis (microvolts), the x-axis represents time from stimulus onset in milliseconds.

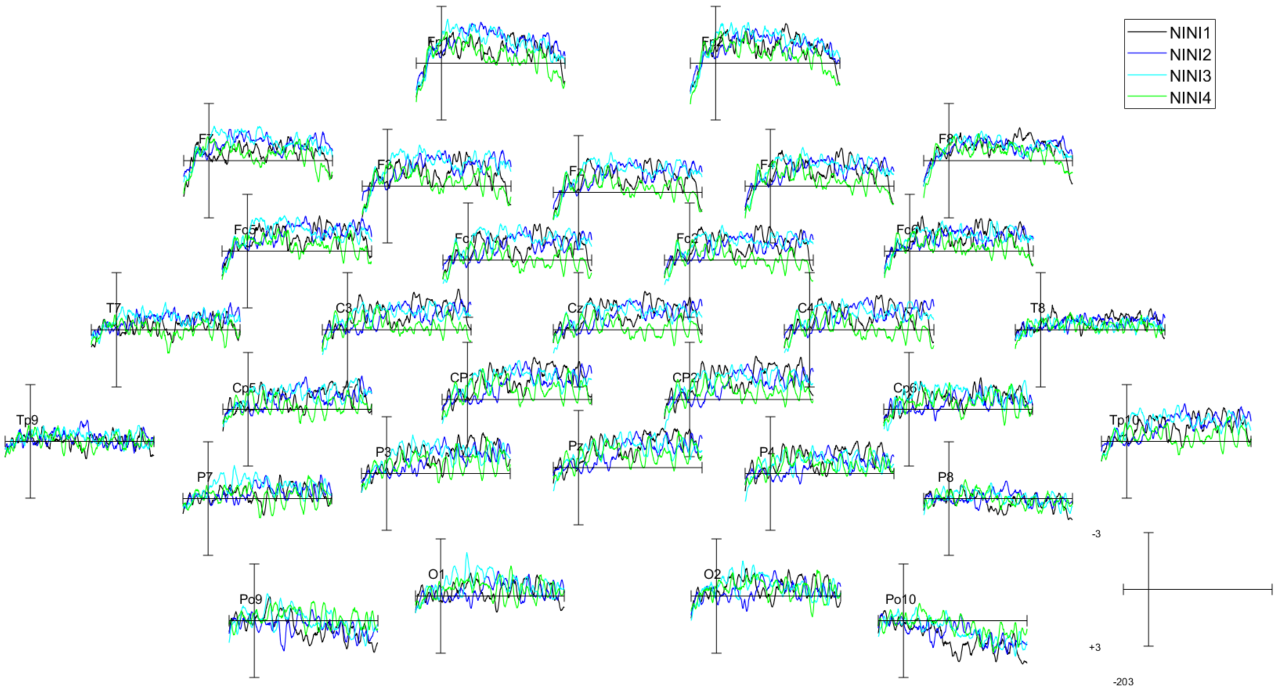

Figure S29 – Grand average ERPs (n=40) of the of the four successive parts, No-Image-No-Image (NINI) trials. Voltage is represented on the y-axis (microvolts), the x-axis represents time from stimulus onset in milliseconds.

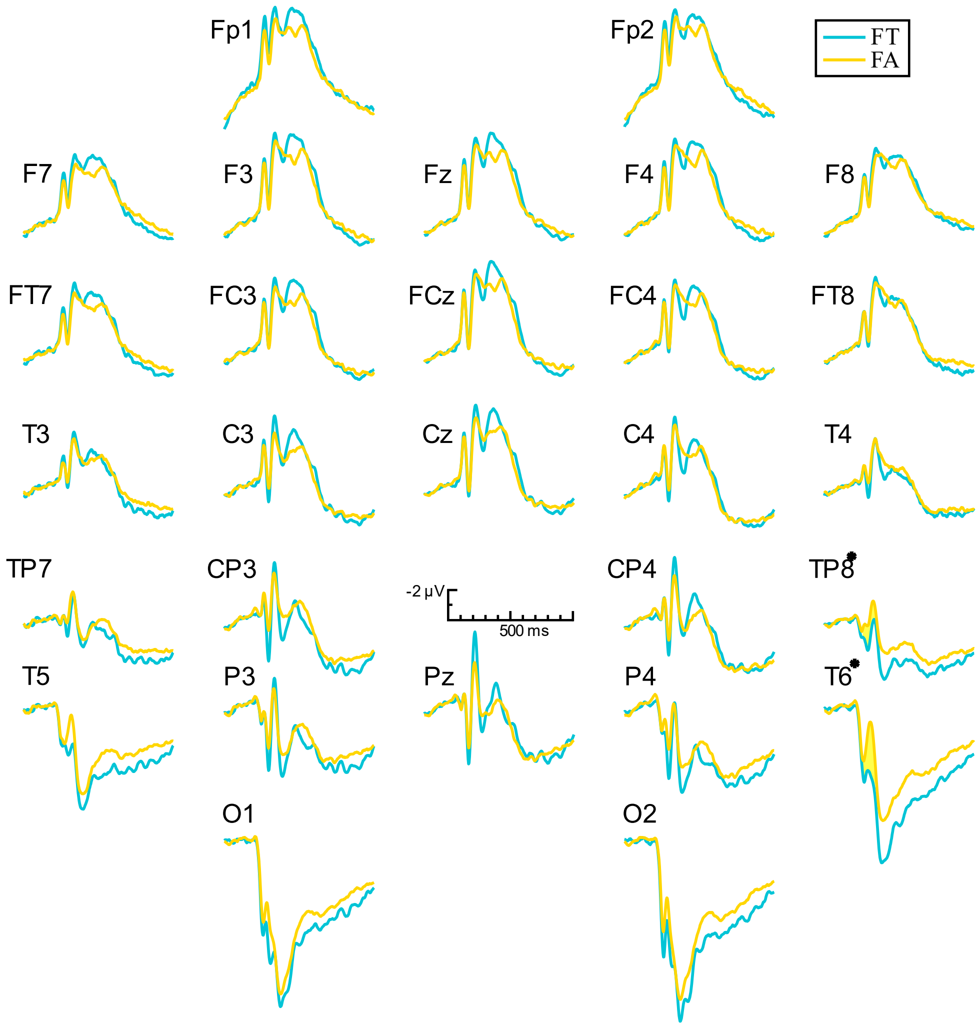

Figure S30 – Grand average ERPs of the main condition mixed (SAD+DAD) separated between participants who reported feeling in the presence of their partner for more than 50% of the time (FT, n=28) and those who didn't (FA, n=36). Voltage is represented on the y-axis (microvolts), the x-axis represents time from stimulus onset in milliseconds. Yellow area indicates a significant difference between the two conditions on the highlighted time-windows, paired sample t-tests (p<0.05).

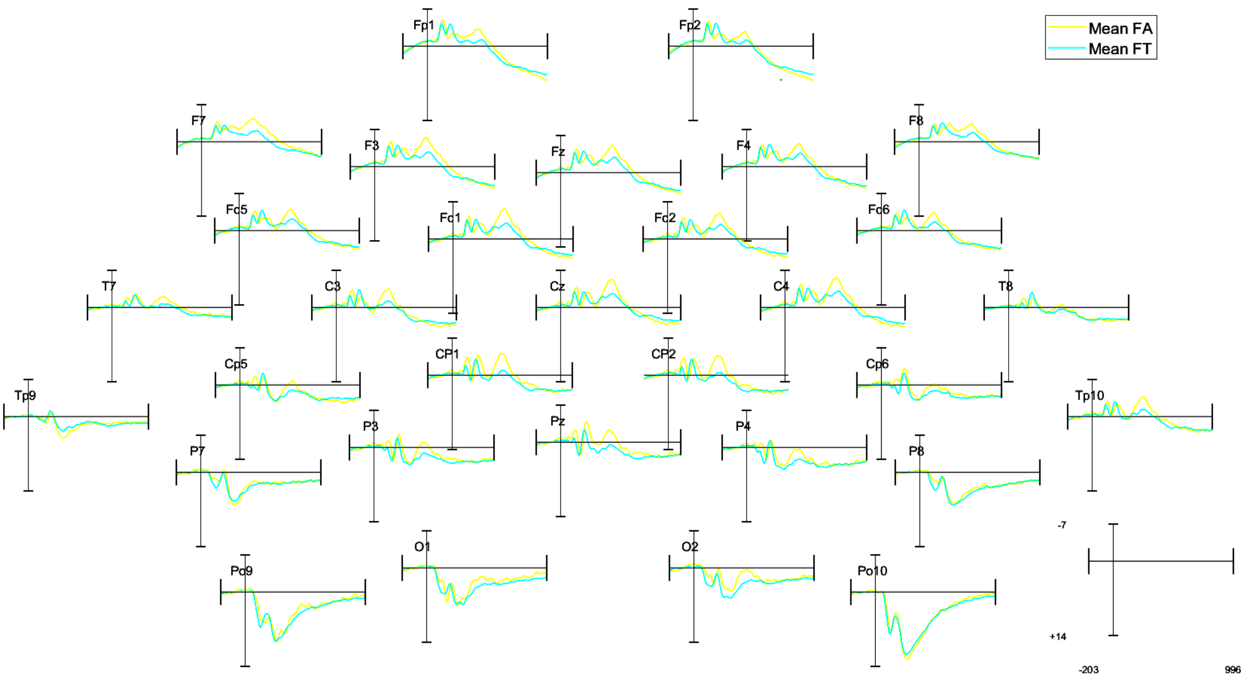

Figure S31 – Grand average ERPs of the main condition mixed (SAD+DAD) separated between participants who reported feeling in the presence of their partner for more than 50% of the time (FT, n=30) and those who didn't (FA, n=10). Voltage is represented on the y-axis (microvolts), the x-axis represents time from stimulus onset in milliseconds.