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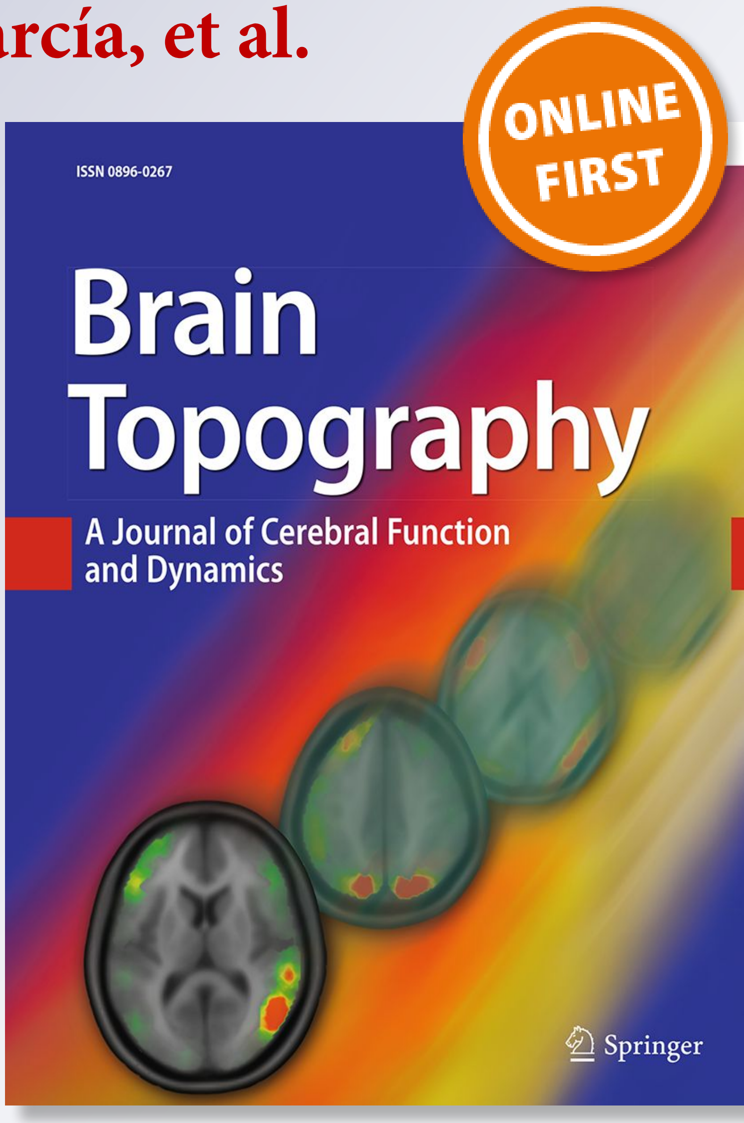

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ORIGINAL PAPER

Neural Dynamics in the Processing of Personal Objects as an Index of the Brain Representation of the Self

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Abstract
Across time, personal belongings incorporate semantic self-knowledge contributing to the subjective meaning of mineness and preference, whose access is prioritized. Although neuroimaging is starting to explore self-knowledge processes, more research is still necessary to better understand many aspects of these processes. One, the timing of the mechanisms involved, is the main purpose of the present study. Here, we investigate the differential patterns of event-related brain potentials and the underlying dynamic causal connectivity between neural generators to self-related objects ranging in self-relevance, as compared to non-personal-related objects. Personal objects elicited lower N2 and higher P3 components compared to non-personal objects, and those with high relevance showed the lowest N2 and the highest P3 amplitudes. Brain sources connectivity corresponding to N2–P3 ERP complex revealed an early connectivity between posterior cingulate/precuneus and parahippocampal gyrus, common for both types of objects. However, this parietal connectivity was kept in later latencies only for personal objects, also intervening the anterior cingulate as the main driver of information flow to the parietal network. Personal objects showed more extensive connectivity between parietal areas and these with anterior cingulate. These findings provide new evidence of a neural connectivity and its temporal course underlying the interplay of lower-level and higher-level cognitive processes relative to personal objects. Further, the results offer new insights on how superordinate mental representations enable distinctive processing of relevant belongings, starting relatively early in time.

Keywords Self-relevance · Object ownership · N2 · P3 · Cortical Midline Structures · Effective source connectivity

Introduction

Several authors concur that the self composes a critical computational system rendering the subjective and unified experience of the world (Gillihan and Farah 2005; Sui and Humphreys 2015). An empirical insight on how that system is organized in the brain is by investigating how the self is contributed by personally familiar objects that surround us, the sense of ownership attached to them, and their relative relevance to us. In this regard, however, as developed below, current literature is still largely inconclusive, particularly in relation to the spatiotemporal pattern of the brain activity associated to personal belongings (e.g. Kim and Johnson 2012, 2014; Turk et al. 2011).

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Self-knowledge and Self-relevance Processing of One's Own Objects

Our self-knowledge comprises all about our physical environment of personal objects or our body parts, but also cognitive states like our own thoughts, leading to the sense of *what belongs to me* (Cunningham et al. 2008; LeBarr and Shedden 2017; Su et al. 2010). The story we configure from the experiences with those events is stored in the semantic self-knowledge. By contrast to general semantic knowledge, semantic self-knowledge is the personally experiences memory about one's own past (Klein and

Nichols 2012; Klein et al. 1999; Schöne et al. 2018). Many of them are significant in one's life, like a special birthday gift or a book that impacted our life. In other words, these stimuli have attached a personal meaning that, in turn, change their perceptual saliency and biases the attentional processes (Sui et al. 2015). After all, it seems obvious that to differentiate self-related from non-self-related events, a basic function of the self-awareness is to discriminate events as personal (experiences related to the self) or non-personal, in relation to their semantic/perceptual knowledge, respectively (i.e., it is *my* car/it is his/her car). This includes autobiographical significant concepts that are highly individual (Conway et al. 2004; Coronel and Federmeier 2016). To the purpose of this work, the processing concerned with the personal-meaning of an object may engage a set of higher cognitive processes (e.g. self-monitoring or evaluating personal knowledge), interplaying with lower cognitive processes (e.g. perception, memory or recognition), along with emotion and reward (Northoff 2013; Sui et al. 2015). We may therefore infer that the concept of self might be the functional interchange between those processes, that Sui and Gu (2017) referred to as the *integrative self*.

To empirically address how the mental structure of the self relates with personal belongings, two effects may be considered, namely *ownership effect* and *self-prioritization* effect (Sui et al. 2012). Such effects relate to a prioritized access when processing a personal-related stimulus (e.g. of all computers, this is mine). Belk (1988) introduced the concept of *extended self*, defined as the effect of associating objects to the self (object ownership) with their respective personal meaning, affective and rewarding value. In his work on mere-ownership effect, Beggan (1992) originally proposed that object ownership leads to a mental association between the owner's self and the owned object. It is well established that the *mere sense of ownership* paradigm primes the access to memory (*increased rewarding value*, Kim and Johnson 2012, 2014). The mere sense of object ownership is a paradigm enabling the participants to transiently acquire a self-object association along the experimental session. Using this paradigm, Kelley et al. (2002) and Tacikowski and Nowicka (2010) found a faster reaction time to self-related stimuli, probably as the result of a preferential access to an enriched mental representation in memory (e.g. Maki and McCaul 1985; Rogers et al. 1977; Symons and Johnson 1997). This enhancement entails deeper encoding of material related to our self (Greenwald and Banaji 1989; Klein and Kihlstrom 1986; Klein and Loftus 1988). These studies evinced that when person-related information is presented, an enlarged deployment of cognitive resources is increased to achieve a better coupling between attention, memory and decision-making in response selection (Sui and Humphreys 2015).

However, alternative paradigms to mere sense of object ownership have been less explored, while they might provide further insights using more enduring and deeper self-object associations. This is the case when the objects truly belong to the individuals and are used habitually. Using real possessions ranging in relevance, each of the experimental objects has a particular attached experience, available in autobiographical memory. The present study uses a paradigm of this sort. Personal relevance of owned objects depends on their affective and rewarding charge attached to the self (Ball and Tasaki 1992; Northoff and Hayes 2011). By virtue of the relevance dimension, that object may be encoded as semantic self-knowledge, that is, as an extension of the self (Gallagher 2000).

What Cognitive Neuroscience Is Unraveling on Self-associated Objects and Their Relative Relevance

Growing evidence on neuroimaging associates self-related processing to a set of medial cortical areas, the so-called Cortical Midline Structures (CMS, Northoff and Bermpohl 2004; Northoff 2013, Northoff 2016a). It has been shown that CMS are critical for both self-relatedness and self-relevance processing, as they are involved in describing the current stimulus in relation to the self (Gillihan and Farah 2005; Northoff 2016a). The CMS consist of cortical areas widely distributed on the medial regions, namely, ventromedial and dorsomedial prefrontal cortex (vmPFC, dmPFC), anterior cingulate cortex (aCC), medial parietal cortex (mPC), posterior cingulate cortex (pCC) and precuneus (PC). Of particular interest is that vmPFC seems to account for the continuous representation of self-referential information. This area is functionally linked to supragenual aCC that holds the current stimulus processing in short-term memory, while it is evaluated as self-related by the vmPFC (Northoff 2016b). The pCC and the PC, in turn, are involved in integrating self-related information to semantic memory in the context of one's own person (semantic self-knowledge).

Regarding personal-related objects processing, several authors have used the mere ownership paradigm of self-object association. In this regard, fMRI studies have explored how participants rate objects that they own as more attractive (more rewarding value) than objects that they do not (Beggan 1992). It has been repeatedly shown that rating the likeability of owned objects activates the mPFC. Gawronski et al. (2007) named this effect *associative self-anchoring*. In an fMRI study, Sugiura et al. (2005) compared personally familiar objects (subject's personal belongings) and personally familiar places with unfamiliar objects and places, to explore their representation in episodic memory. They found that the brain mechanisms of episodic memory retrieval of personal spaces and objects rely not only in mPFC but also in the pCC and the PC. This pattern of activation may be related to a richer contextual (personal) information linked to that sort of stimuli.

The Brain Dynamics of Person-Related Objects and Relevance Processing: The Present Study

Electroencephalographic (EEG) studies provide valuable information in the time and frequency domains. Miyakoshi et al. (2007) studied the effects of self-relevance in participant-owned objects in a recognition task. They observed that a negative fluctuation at about 250 ms (the N250 component) distinguished familiar and self-relevant objects from unfamiliar objects. A P3 dissociated high from low self-relevance, as an index of higher-order cognitive processes. Turk et al. (2011) evaluated the ERP modulations to selective attention demands in a task of self-relevance attribution. In this task, a mere sense of ownership paradigm served to associate an object to the participant or to the experimenter. It was reported an increase of the parietal P3 amplitudes to self-related objects, which was interpreted as an increased visuospatial attentional processing when evaluating an object as self-related. More recently, Xu et al. (2017) explored how the relevance of self-related information impacts on neural activity. They observed higher early attention resources devoted to discriminate highly important self-related content compared to minimally important, as revealed by an enhanced P200 amplitude and a smaller N2. Similar results on the N2 component have been observed for self-related stimuli, like names (Chen et al. 2011) and faces (Guan et al. 2014). Moreover, Xu et al. (2017) observed that the P3 amplitude was also higher to highly important content compared to moderate and minimally important, indexing complex cognitive evaluation of the meaningfulness of self-relevant information (Johnson 1986).

Complementary to ERPs, ongoing non-phase locked EEG oscillations may be of interest on how different brain areas are engaged in person-related information processing. One of the most replicated findings is the alpha suppression (event-related desynchronization, ERD, 8–13 Hz) in sensory-motor areas due to the relatively high salience of self-related stimuli (own body parts, Evans and Blanke 2013; hearing own name, Höller et al. 2011; and personal traits, Mu and Han 2013). Moreover, this alpha ERD has been related to externally oriented attention (Klimesch 2012). Gamma oscillations synchronization (30–60 Hz) has been found in the posterior CMS hubs (PC/pCC) during recollection from autobiographical memory (Foster et al. 2012). Theta oscillations have been also affected in the anterior hub (mPFC, ACC). For instance, Miyakoshi et al. (2010) found an intertrial coherency decrease in the theta and alpha band to own face images in the time window 170–290 ms, likely indicating reduced functional demand within the right fusiform area. Different areas involved in these processes should be interconnected. However, there is still a lack of studies disentangling such dynamics analyzing the effective connectivity at different coupling oscillations between the underlying brain sources. To explore how brain sources are functionally intertwined, dynamic causal modelling may be used (multivariate autoregressive modeling, e.g. Geweke 1982; Granger 1969). Granger causality quantifies reciprocal interactions between pair of sources, that is, directed influence of source activity A on source activity B, and reciprocally. Up to date, studies that have explored the temporal dynamics of self-relatedness processing using EEG are still scarce.

The present work aimed to study the temporal and spatial dynamics of the brain activity relative to the processing of personally familiar objects and non-personal objects. Towards this end, we proceed in a two-step procedure: (a) analysis of the event-related potentials to both personal and non-personal objects and their relative relevance, and (b) analysis of the directed flow of information between the brain sources involved. We expect that the identification of personal objects may involve the access/retrieval to memories of past experiences, which will not occur to unknown objects. Based on the reviewed literature, we hypothesize a smaller N2 component to personal objects compared to non-personal objects, still more in those with the highest relevance, as a reflection of lower deployment of attentional resources. At later latencies, we hypothesized that P3 amplitude modulation would be larger to personal objects compared to non-personal ones and, again, even larger to highly relevant objects, as an index of the extended access to neural networks representing semantic self-knowledge. To accomplish a more comprehensive description of these processes, we will study the pattern of connectivity within and between anterior and posterior areas of the CMS. In particular, we expect higher effective connectivity across time in the posterior areas (pCC, PC) related to the access to personal-knowledge memory. The fact that personal objects might involve the recruitment of semantic self-knowledge and emotional content to make personal attribution, lead us to suppose that the anterior hub may be also intervening in higher-order processing (anterior cingulate and mPFC).

Materials and Methods

Participants

Twenty healthy graduate and undergraduate students (12 females) participated in this study, with an age range of 19–39 years (mean 24,9 ± 4,8 years). They all were right-handed (mean Oldfield scores of +84) and declared normal or corrected-to-normal vision. Written informed consent was obtained from all participants. All experimental procedures were carried out following the Declaration of Helsinki and the study was approved by the ethics committee of the Complutense University.

Stimuli

Two weeks before the EEG session, the participants selected 15 personal objects that they categorized as either high (5), mid (5) or low (5) in relevance based on utilitarian (personal laptops, wallets) or emotional (rings, bracelets) criteria. On average, time of belonging of personal objects was 6.8 years (±2.5). The owners have been used their objects in a wide range from several times a year to habitually or daily. The non-personal objects were never used. Therefore, the stimuli were categorized by their ownership, i.e., as personal or non-personal, as well as by their relative relevance or personal meaning (high, mid or low). They were asked to provide digital high-resolution photographs of their selected personal belongings. Each picture depicted a single object, avoiding persons, animals, or multi-object pictures (albums, collage, etc.). All digital photos were edited with Photoshop® to remove the background and to homogenize their luminance (personal images: $L = 68.2 \pm 28.4$; other images: $L = 87.2 \pm 42.5$). To standardize the dimensions of the images, the original aspect ratio was rescaled to 480 pixels width or 640 pixels height.

For each participant, fifteen additional pictures conformed the pool of non-personal stimuli, selected from objects belonging to the other participants (see Fig. 1 for some examples). Both personal and non-personal objects were always matched in semantic category (e.g. personal laptop vs other's laptop). Each object was randomly presented 10 times to increase the signal-to-noise ratio. Therefore, each participant was presented with a total of 300 trials (15 objects × 10 presentations × 2 ownerships: personal, non-personal). The EEG session lasted around 30 min, including two brief resting periods. The whole experimental session lasted 1.5 h.

Experimental Procedure

The participants comfortably seated in front of a computer screen (distance 70 cm) in a dimly-lit, sound-attenuated and electrically-shielded room. Each trial started with a fixation cross presented centrally, white on a black background, for 500 ms and then one object was presented for 1000 ms. After that, the image was replaced by a black screen for 2 s. The task consisted of observing the stimuli and deciding as quickly and accurately as possible whether the presented object belonged to the participant or not, by pressing one of either two buttons (Yes or No). Such buttons were counterbalanced between index and middle fingers of the right hand. Each session included two short breaks to rest.

EEG Recordings and ERP Analysis

Continuous EEG was recorded from 59 scalp Ag/AgCl electrodes according to the international 10–20 system. These electrodes, as well as one electrode at the left mastoid, were initially referenced to the right mastoid, and later referenced off-line to the mean of left and right mastoids. The vertical electrooculogram (VEOG) was recorded from below vs. above the left eye, whereas the horizontal electro-oculogram (HEOG) was recorded from positions at the outer canthus of each eye. Data were sampled at a rate of 250 Hz, and a band-pass of 0.01 to 100 Hz (12 dB/oct). All electrodes impedance was kept below 5 kΩ. EEG data analysis was performed using EEGLAB v14.1 (Delorme and Makeig 2004; http://www.sccn.ucsd.edu/eeglab) running under Matlab R2017b (MathWorks, Natick, MA, USA). A Hamming windowed FIR filter of 0.1–40 Hz was applied to continuous EEG data. EEG data were segmented into epochs starting 200 ms prior to and ending 1000 ms after the stimulus onset. For averaged ERPs, the baseline mean activity was applied between

Fig. 1 Examples of stimuli presented in the experiment

− 200 and 0 ms relative to stimulus onset. Only EEG data of correctly responded trials were included in each dataset. EEG data were visually inspected to remove transient artifacts (brief head movements, temporally noisy or drifting electrodes). Moreover, an Independent Component Analysis (ICA) was applied to estimate 64 independent components (ICs) for each participant. This analysis uses a deflationary method by which ICs were obtained one-by-one following a fixed-point iteration scheme (fastICA algorithm; Hyvärinen 1999). From the overall ICs, we applied a semi-automated procedure described by Chaumon et al. (2015). This procedure assists with statistical criteria to select artifacted ICs due to eye movements, muscle contractions, line noise or electrode misconnections. After selecting the artifacted ICs, they was dropped out from the EEG data from all electrodes. The overall rejection rate was 4.18% of EEG epochs. Mean number of segments to personal and non-personal conditions were 145 and 142.4, respectively. This difference was not statistically significant ($F_{1,19}=3.2$; $p=0.1$; $\eta_p^2=0.1$). To personal objects, mean number of segments to high, medium and low relevance were 48.7, 48.0 and 48.2, respectively. To non-personal objects, 47.6, 47.1 and 47.8, respectively. This difference was not statistically significant neither between kinds of objects ($F_{1,19}=2.5$; $p>0.1$; $\eta_p^2=0.12$), nor between levels of relevance ($F_{2,38}=0.4$; $p>0.5$; $\eta_p^2=0.02$). For statistical analyses (ANOVAs), two separated repeated-measures ANOVAs, namely, N2 (250–312 ms) and P3 (370–570 ms), were performed for testing the effects of ownership (Personal, Non-personal) and relevance (High, Medium, Low). ROIs were grouped into two factors: Anterior–Posterior axis (AP axis; with three levels: anterior, central and posterior) and Left–Right axis (LR axis; with the three levels: left, midline and right). We averaged the electrodes into the following brain regions of interest (ROIs): Right-frontal (Fp2, AF4, F2, F4), Mid-frontal (Fz, Fpz), Left-frontal (Fp1, AF3, F1, F3); Right-central (FC2, FC4, C2, C4), Mid-central (FCz, Cz), Left-central (FC1, FC3, C1, C3); Right-parietal (CP2, CP4, P2, P4), Mid-parietal (CPz, Pz), and Left-parietal (CP1, CP3, P1, P3). The Greenhouse and Geisser procedure was used to compensate for violations of the sphericity assumption, when appropriate. For both behavioral and ERP data, partial eta-squared η_p^2 and statistical power) is indicated as a measure of effect size. Bonferroni correction was used in post hoc analyses for multiple comparisons. Moreover, False Discovery Rate (FDR) was also applied when appropriate. FDR procedure is suitable for a reasonable correction on a large number of comparisons, as is the case in time-by-time permutation-based statistics.

Brain sources were computed also using ICA (namely, Infomax algorithm; Bell and Sejnowski 1995) from the artifact-free EEG epochs across participants and experimental conditions. A set of ICs that accounted for at least 95% of the averaged ERP signal were selected to perform effective connectivity analysis. Their scalp maps (not showed) were compatible with physiological source distribution and temporally distinct time courses (Onton et al. 2006). Scalp projections appeared like single equivalent dipoles, whose locations were computed using DIPFIT toolbox (under EEGLAB v14). Best-fitting equivalent dipoles were listed in Table 1.

Source Information Flow Modeling

Independent component time-series were forwarded to a *multivariate effective connectivity analysis* in the source domain. This analysis was carried out fitting our data into a segmentation-based adaptive autoregressive model using the Viera–Morf algorithm [implemented by Source Information Toolbox (SIFT) from EEGLAB v14; Delorme et al. 2011; Mullen 2014]. Such a model tries to find the simplest possible network graph explaining the directed information dependencies between the extracted dipoles (statistical causation, Wiener 1956). For each epoch, a model order of 13 was applied within a 148 ms sliding-window with a step size of 28 ms. This was applied to 2901 segments in the personal condition and 2851 segments in the non-personal condition. After testing the stability and residual whiteness (autocorrelation function -Portmanteau, ACF test of uncorrelated residuals: $p<0.05$), the model coefficients allow us to obtain the time–frequency (TF) distribution of the nDTF coefficients (normalized direct transfer function, Korzeniewska et al. 2008). Moreover, it may allow to represent the cross-connectivity measures in the range of 1–40 Hz TF between the seven ICs (Table 2). As we already outline, TF technique allows measuring ongoing EEG non-phase-locked oscillations. For statistical analysis, a percentil threshold of 95% was used for each frequency to visualize relevant, non-zero directed connections between brain areas (also see Baccalá et al. 2006). For each frequency, Fig. 3 plots

Table 1 Independent components that accounted for more than 95% of the overall variance

ID	Talairach coord. (X,Y,Z)	RV (%)	Pvaf	Brain area
IC1	15, − 25, 2	7.7	40.7	Parahippocampal gyrus
IC2	− 6, − 75, 41	5.2	4.3	Precuneus
IC3	− 5, 69, − 30	13.9	9.56	oPFC
IC4	− 9, 1, 27	7.3	8.09	dCC
IC5	0, 18, 11	3.8	13.5	aCC
IC6	− 6, 11, − 12	13.4	3.0	Subcallosal area
IC7	10, − 56, 13	6.2	61.9	pCC

IC1—Parahippocampus, IC2—Precuneus, IC3—Orbital Prefrontal Cortex, IC4—Dorsal Cingulate, IC5—Anterior Cingulate, IC6—Subcallosal cortex, IC7—Posterior Cingulate

RV residual variance, *Pvaf* Percent of data variance accounted for by each component

Table 2 Statistical analysis of ownership and relevance effects to each ERP component

Factors (df)	N2–F (η_p^2, π)	P3–F (η_p^2, π)
Ownership (1,19)	19.3*** (0.5, 0.99)	60.6*** (0.76, 1)
Relevance (2,38)	n.s.	n.s.
Ownership × relevance (2,38)	3.4* (0.16, 0.63)	n.s.
AP axis (2, 38)	50.2*** (0.72, 1)	27.4*** (0.59, 1)
LR axis (2, 38)	24.3*** (0.56, 1)	12** (0.39, 0.97)
Ownership × AP axis (2, 38)	3.9* (0.17, 0.67)	3.7* (0.16, 0.65)
Relevance × AP axis (2, 38)	n.s.	n.s.
Ownership × LR axis (2, 38)	n.s.	3.7* (0.16, 0.56)
Relevance × LR axis (2, 38)	4.3** (0.19, 0.77)	3.7* (0.16, 0.75)
Ownership × AP axis × LR axis (4, 76)	n.s.	6.1** (0.24, 0.93)
Relevance × AP axis × LR axis (4, 76)	2.1† (0.1, 0.63)	n.s.

†p < 0.1, *p ≤ 0.05, **p ≤ 0.005, ***p ≤ 0.0005

only values larger than 95% of all other measured values at that frequency. For each cell, we computed the envelope of the two-sided thresholds for statistical significance (using the percentile threshold, not shown). Values between the threshold lines are considered as non-significant and masked in the TF plot. In Fig. 4 the same non-parametric statistical method was applied. In this case, the values of the estimator (connectivity strength or amount of information along the edge, connectivity magnitude, asymmetry ratio of connectivity and the amount of information flow—see Mullen 2010 for more info) were compared to the quantiles of the null distribution. If the estimator exceeds a critical value of the null distribution (95%) of the samples, the estimate will be considered significantly non-zero at the level of $p < 0.05$.

Results

Behavioral Results

Participants' hit rates (accuracy) were very high (96.9%, SD = ± 2.1%) compared to omissions and misclassifications (1.5%, SD = 1.5%; 1.5%, SD = 1.2%, respectively). The difference in RT between personal objects (M = 559.8, SD = 42.3) and non-personal objects (M = 583.5, SD = 47.2) showed a statistical difference ($t_{19} = -4.8$, $p < 0.001$).

Electrophysiological Results

Event-Related Potentials to Personal and Non-personal Stimuli

Figure 2 (left panel) depicts the average waveforms to personal and non-personal conditions, at their respective relevance as evaluated by the object's owner. A visual inspection of the grand averages to each condition reveals a main difference in the N2 component, followed by a long-lasting positive component (P3). Maximal differences between personal vs non-personal objects were found in the 250–312 ms (N2) and 370–570 ms (P3) time-windows. Although the long-lasting positivity seemed to continue for a longer period, at least at certain electrodes, our analyses will end at 570 ms given that mean RTs occurred around that value. ERP modulations to personal relevant objects were slightly different, while those to non-personal objects remained without apparent differences. On the right panel, topographical maps at both time-windows reveal a differential distribution, that is, N2 was mostly mid-frontal and P3 broadly-central.

In the N2 window, as shown in Table 2, a significant main effect of ownership was observed. As predicted, the N2 amplitude was significantly smaller (M = 0.56 μV) to personal objects compared to non-personal objects (M = − 1.1 μV). The interaction ownership by A–P axis revealed that non-personal condition elicits more negative potentials compared to personal condition, respectively, at frontal (M = − 3.1 μV vs M = − 1.1 μV) sites, followed by central (M = − 2.8 vs M = − 0.9) and parietal (M = 2.57 vs M = 3.68) regions; all *ps* < 0.001. The main effect of relevance failed to reach statistical significance, but it did in interaction with ownership, meaning that the differences in amplitude to each level of relevance were significant between personal and non-personal objects: high, 2.3 μV; medium, 1.4 μV and low: 1.2 μV, respectively; all differences with *ps* = < 0.01. Apparently, N2 to highly relevant personal objects elicited the lowest amplitude. To test whether the N2 amplitude was different between high and low relevance conditions, we applied a time-by-time permutation-based statistics to compare both conditions. This revealed that N2 amplitude showed a slight but significant decrease (statistical threshold to $p < 0.05$, correcting for multiple comparisons using FDR) to high relevance compared to low relevance at frontal electrodes (F3 and F4). The interaction relevance by L–R axis reveals that N2 elicited a greater negativity at central sites compared to left and right sites.

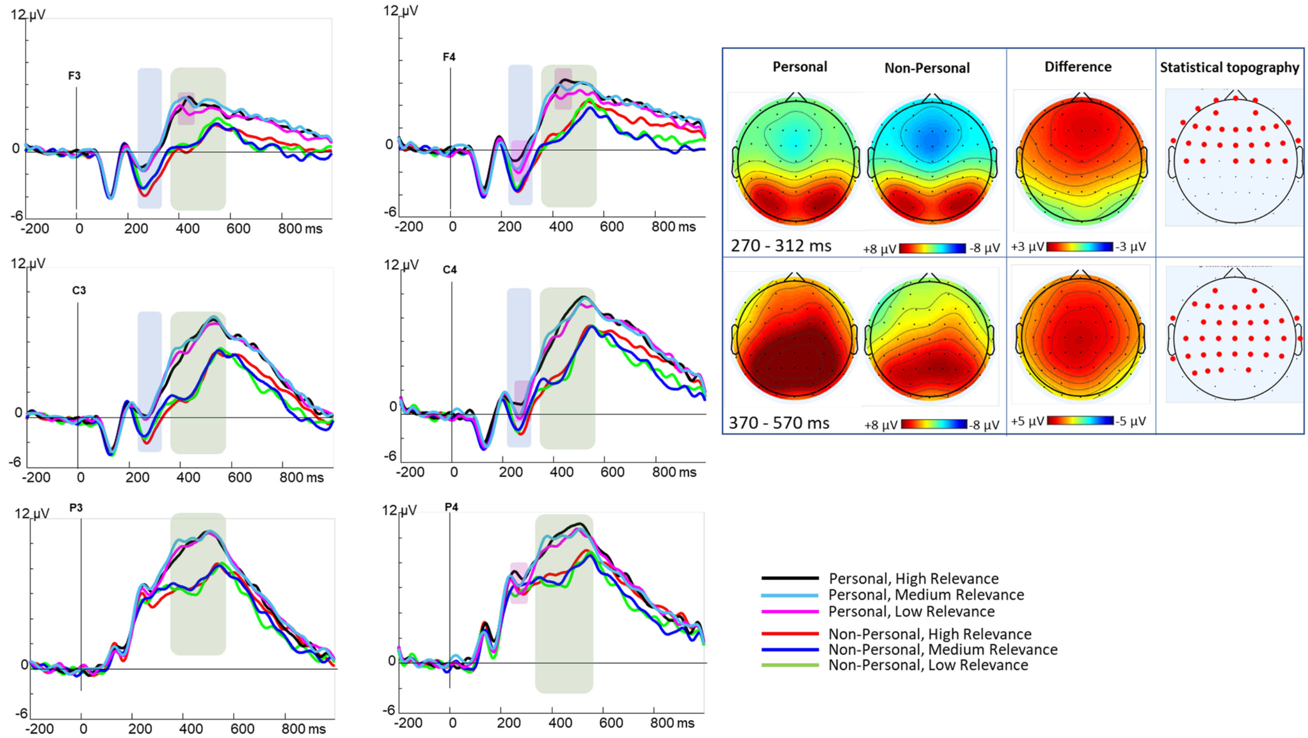


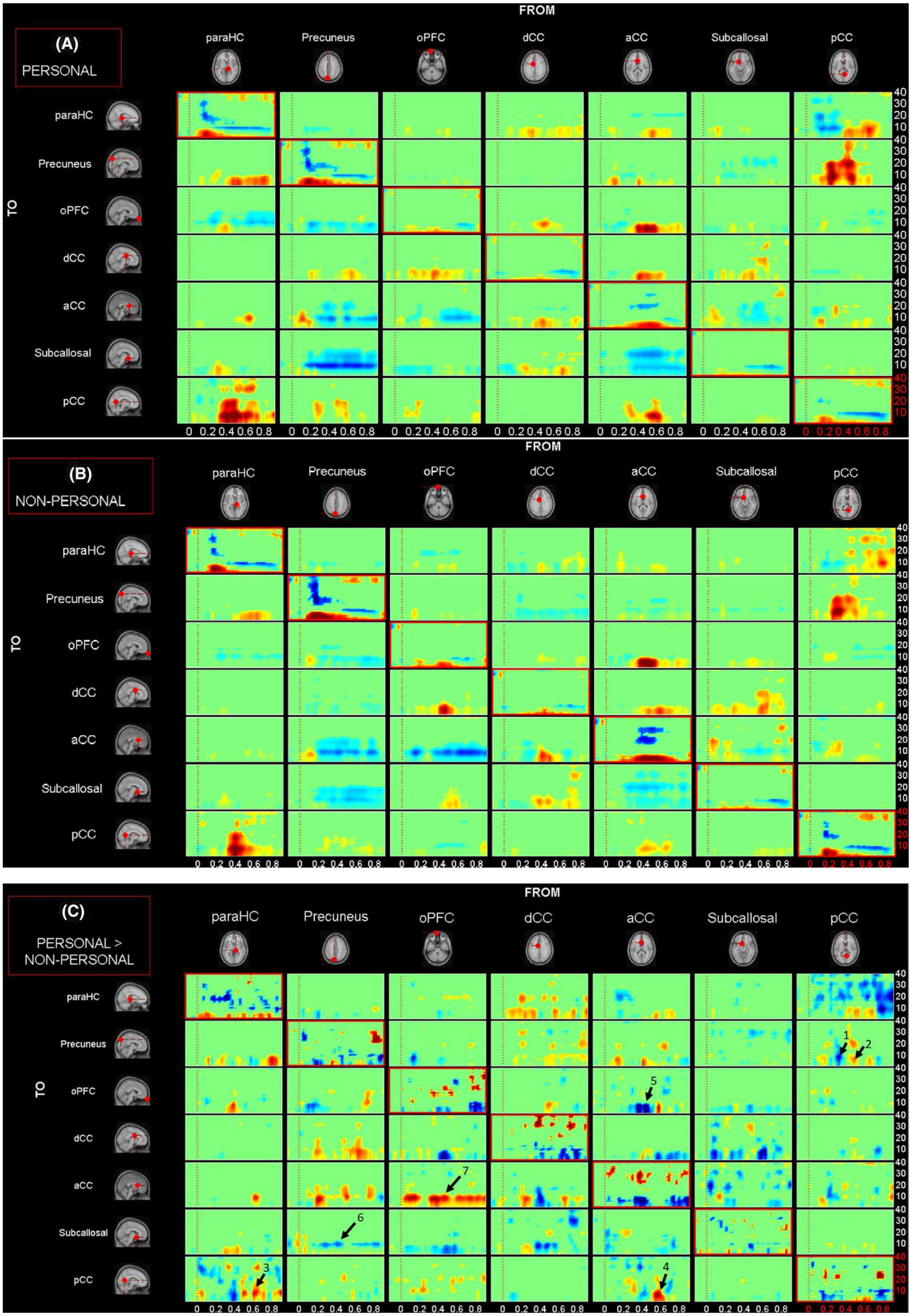
Fig. 2 Left panel Average waveforms to personal vs non-personal objects at their respective relevance. Boxes in color indicate the latency period corresponding to N2 (blue) and P3 (green) at which amplitude differences reached statistically significance (p < 0.05). Violet boxes indicate statistical differences between high and low relevance for personal objects. Right panel *Left most*—Topographical maps to each condition and the difference waves at the selected time-windows. *Right most*—Statistical topographic maps based on a Student's t computed for each electrode. Only significant electrodes ($p < 0.05$, corrected for multiple comparison, FDR) are depicted

The P3 component showed a statistically significant main effect of ownership, reaching the highest amplitude to personal objects (M = 7.2 µV) compared to non-personal objects (M = 3.8 µV). The interaction ownership by A–P axis revealed a positivity increasing from frontal to parietal sites (in all pair-wise comparisons $ps < 0.001$) in both conditions. Moreover, positivity was larger to personal condition than non-personal condition, respectively, at frontal (M = 3.9 µV vs M = 1.1 µV), central (M = 7.2 µV vs M = 3.4 µV) and parietal sites (M = 10.4 µV vs M = 6.8 µV), all pair-wise comparisons with $ps < 0.001$. Moreover, in the personal condition, the interaction ownership by L–R axis revealed that positivity at right sites showed significantly decreased (M = 6.6 µV) compared to left and midline sites that were not different between both (M = 7.5 µV vs M = 7.4 µV, $p > 0.5$). In non-personal condition, while positivity at right sites appeared also decreased relative to personal condition, left sites showed increased positivity compared to midline sites (M = 4.3 µV vs M = 3.8 µV, $p < 0.05$). Finally, the interaction relevance by L–R axis showed statistical significance, revealing that relevance elicits a reduced positivity at right sites compared to left and midline sites (all $ps < 0.05$), being the latter not significantly differing ($p > 0.5$).

In the P3 time window, neither the main effect of relevance nor in interaction with ownership were significant. We repeated the ANOVA now reducing one level of relevance (the intermediate level). The ANOVA tested the triple interaction ownership by relevance by AP axis, but was marginally significant ($F_{2,38} = 3.3$; $p = 0.07$; $\eta_p^2 = 0.15$). Such not significant result may be explained by the relatively constrained time window of the ERP effect. Therefore, we explored further this effect by applying a time-by-time permutation-based statistics to compare both conditions, revealing that P3 amplitude showed a slightly but significant increase (statistical threshold to $p < 0.05$, correcting for multiple comparison using FDR) to high relevance compared to low relevance at frontal electrodes (F3 and F4).

Source Information Flow Analysis of the Neural Activity for Personal and Non-personal Objects

The analysis of effective connectivity aimed to test whether personal vs non-personal objects might show a different pattern of connectivity between the underlying


(A)
PERSONAL
FROM
TO
paraHC
Precuneus
oPFC
dCC
aCC
Subcallosal
pCC
(B)
NON-PERSONAL
(C)
PERSONAL >
NON-PERSONAL
0 0.2 0.4 0.6 0.8
40
30
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◂**Fig. 3** TF distributions of information flow between pairs of brain sources in personal (**a**) and non-personal conditions (**b**) (origin: upper columns, destination: left rows). **c** Plots the contrast Personal > Non-personal. Warm-Cold colored pixels indicate increment and decrement, respectively, of information flow between sources. Frequency is on the y-axis (linear, 1–40 Hz) and time on the x-axis (− 200 to 1000 ms). Arrows indicate main results on TF, described in the text

brain sources. The connectivity analysis was performed in two steps: *TF transfer distribution* and *graphical model of effective connectivity*.

Time-Frequency Transfer Distribution

The connectivity distribution estimated by normalized Directed Transfer Function (nDTF) are depicted in TF grids in the frequency range of 1–40 Hz relative to the baseline period to personal vs non-personal conditions (Fig. 3a, b). Each cell in the grid depicts the TF distribution of nDTF values that may be interpreted as frequency-domain conditional Ganger Causality across time, frequency and anatomical source pair. Therefore, the TF distribution represents the amount of information that flows between the corresponding pair of sources from X (column) to Y (rows), and normalized by the total amount of causal outflow from X. As the magnitude of the nDTF values are represented relative to the baseline window (− 200 to 0 ms), warm-colored pixels denote transient increment of information flow from X to Y (high synchronization at that frequency) as compared to the baseline, and cold-colored pixels denote decrement information flow (low synchronization). Cells of the diagonal represents auto-connectivity or intrinsic dynamics of a source, that is, the degree to which that source is driving itself (not related to causal input from other sources). Figure 3c depicts the contrast personal > non-personal conditions over the common baseline window.

The following summarizes only statistically significant results from the contrast Personal > Non-personal:

(1) Pair pCC–PC: it showed a significant increase of flow of information from pCC to PC in the 238–322 ms time-windows in theta band (4–7 Hz) in the non-personal condition compared to personal condition (1 in Panel C). However, later around 462 ms, this theta band connectivity between pCC and PC showed an increment of flow in personal compared to non-personal objects (2 in Panel C). In fact, at this later latency, this sort of coupling was not observed in non-personal condition (Panel B). Beta band (20 Hz) was apparent but not significant.

(2) Pair paraHC–pCC: it reveals a theta-band and beta-band connectivity between paraHC and pCC in both conditions around 450 ms time-window, but personal condition showed a significant increase in the theta band (4–7 Hz) at later latencies (around 576 ms, 3 in Panel C). Although beta band (20 Hz) was apparent, this was not significant.

(3) Pair aCC–pCC: it reveals an increase of theta-band connectivity between aCC and pCC (6 Hz) in the 500–600 ms time-window (maximum at 576 ms, 4 in Panel C).

(4) Pair aCC–oPFC: it reveals an increase of information flow in the theta band from aCC to oPFC around 350–434 ms time-window to non-personal condition (5 in Panel C).

(5) Pair PC-subcallosal area: it showed a long-lasting alpha (10 Hz) suppression (200–900 ms, 6 in Panel C) between PC and subcallosal sources that was increased in personal objects.

(6) Further, suppression in the alpha band was also found between oPFC and aCC in the 200–800 ms time window, which was higher in non-personal condition compared to personal condition (from oPFC to aCC, 7 in Panel C), but this did not survive the statistical threshold.

Graphical Model of Effective Connectivity

Derived from the TF information, Fig. 4 depicts the overall evolution of the cortical network dynamics, measured by asymmetry ratio (color of the node: red = causal flow, blue = causal sink) and connectivity flow (color of the edge: amount of information flow) between brain sources applied to our source matrices in three time-frames at 294 ms, 406 ms and 518 ms, where the ERP effects were maximum. Only significantly non-zero parameters are shown, if the lower edge of the 95% CI of its baseline-substracted value is greated than zero. Around 294 ms, this model plots near identical coupling in both conditions between pCC and PC, that is, the node representing the pCC drives information over the PC. It is noteworthy that there was no significant coupling in the anterior hub. Next time-frame (406 ms), the pCC and PC remained coupled, and the paraHC was strongly driving information to the pCC in the personal condition compared to non-personal. Interestingly, around this latency, anterior hub modulated the posterior hub evidenced by an increased significant connectivity from aCC to the PC (personal condition) and the pCC (other condition). In personal condition, aCC showed larger transference to the posterior hub compared to the non-personal condition. In turn, the aCC showed significant coupling to the oPFC in both conditions, though aCC showed larger outflow in the personal than in the non-personal conditions. It also appeared that dCC participated in larger extent along with aCC and oPFC in the non-personal condition compared to the personal condition. Finally, around 518 ms, the personal condition showed higher coupling between posterior nodes (PC, pCC

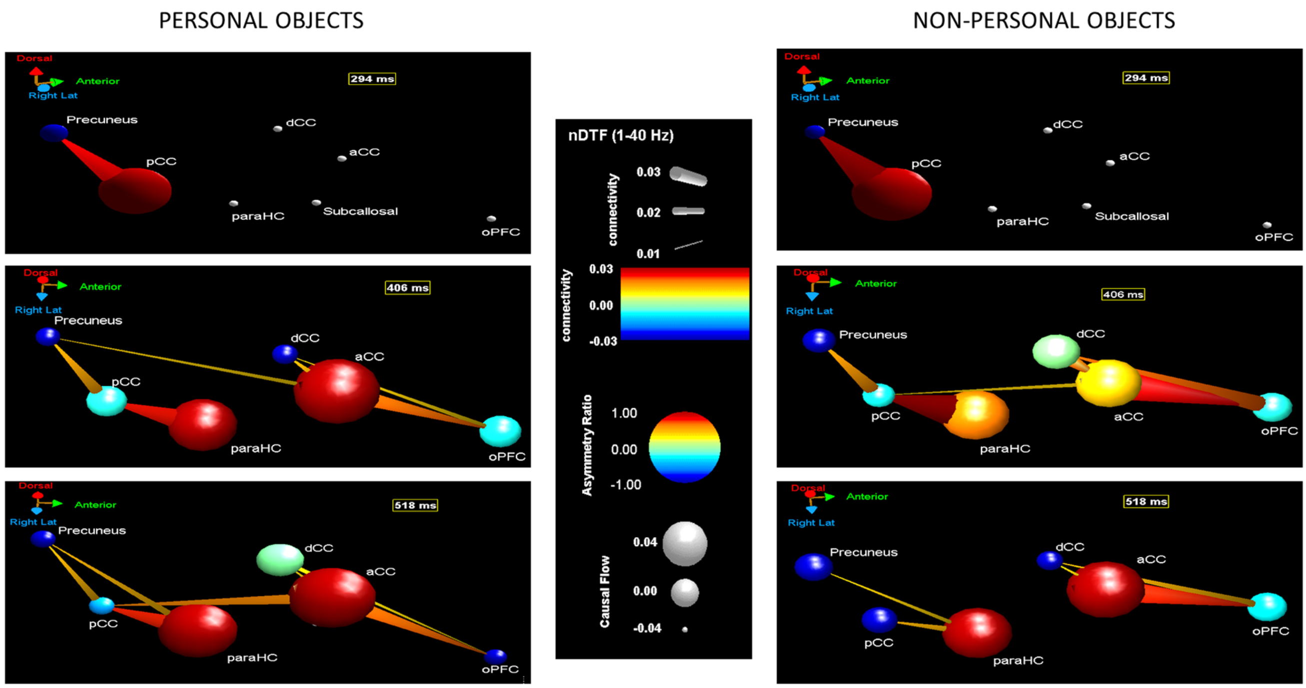

Fig. 4 Dynamic evolution of cortical networks at three frames involved in self-related and non-personal objects processing. The color of the edges represents the amount of flow information among connectivity: Red = high and Blue = low. The size of the edges represents connectivity strength. The color of the nodes represents the asymmetry ratio of connectivity for that source (red = causal source and blue = causal sink). The size of the node represents the amount of information outflow from the source

and paraHC), that is, the paraHC enlarged its activation directly to the PC and pCC, both being also connected. This pattern of connectivity was not observed in the non-personal condition. Finally, while the aCC is strongly driving information to pCC and to oPFC, the latter connection was missing in the non-personal condition.

Discussion

The purpose of this study was to examine the temporal dynamics of the brain activity related to the processing of personally familiar objects ranging in self-relevance, in an object ownership judgment task. ERP and brain sources connectivity patterns reported in this work exhibited a different pattern of neural activity between owned objects compared to non-personal objects. Such pattern may be due to a particular access to and retrieval of semantic personal knowledge associated to the own objects, which is absent in non-personal objects. Specifically, the N2 was able to differentiate between personal from non-personal objects of different relevance. The P3 amplitude was larger to personal high relevant objects. The underlying brain sources were distributed in anterior and posterior brain areas, mostly covering some of the Cortical Midline Structures (CMS). From such distribution, we modeled the effective connectivity just for comparing personal vs non-personal objects, by means of multivariate autoregressive model. This model revealed similarities and differences in the pattern of connectivity between both conditions at different stages of processing. We discuss these findings in detail in the following sections.

Behavioral Findings

Behavioral results clearly support a differential pattern of responses in object ownership judgements. Participants exhibited shorter reaction times to own personal objects than to other objects. In the literature, this is a common finding, probably reflecting a preferential access to semantic self-knowledge (with adaptive or affective value) (Golubickis et al. 2018; Miyakoshi et al. 2010; Sui and Humphreys 2015). For instance, Tacikowski and Nowicka (2010) observed faster reaction times to self-face and self-name than non-personal stimuli (famous or unknown faces and names). They interpreted this effect as a preferential status of attentional resources to enhance the discrimination between personal or related vs non-personal or unrelated material. In studies focusing on self-relatedness, the same effect has been reported to personal traits or faces that have been acquired implicitly (e.g. Ma and Han 2010; Sui and Humphreys 2015).

An Early Identification of Owned Objects Involves the Coupling of Posterior Areas

The mid-frontal N2 component attenuation to personal objects may be reflecting a facilitated access to stored representations of semantic self-knowledge, particularly to those with personally meaningful context (emotional, usefulness). The N2 has been described as an index of higher-order processing, i.e., an early discrimination and categorization of the relevance of self-related stimuli (Patel and Azzam 2005). Interestingly, some authors have established in the N2 the temporal limit between automatic and controlled processing stages (Carretié et al. 2004). Our finding agrees with those reported by Xu et al. (2017) and Chen et al. (2011) that also observed a decrease of the N2 amplitude to highly important self-related stimuli. This may suggest that highly relevant self-related content is easier to retrieve from autobiographical memory, consuming less cognitive resources. It may be argued therefore that important meaning of object ownership can be accessed automatically in self-relative judgments.

It is also possible that the N2 to the personal objects would be partially overlapped with the P3 onset in this condition. This overlap would be unraveled by the connectivity model. At a first instance, the increase in amplitude of this component (N2) to non-personal objects concurs with a higher transference of information from the pCC to the PC, revealed by a significant higher coupling in the theta band (7 Hz). Later on, only for personal objects such connectivity evolved in time to the onset of the P3 (350–400 ms) concurring with an increase in the transference of information from pCC, PC, and paraHC. In this regard, paraHC is also enrolled along with pCC/PC later in time (450 ms) transferring activation to pCC in the theta band (7 Hz) in both conditions, but significantly more to personal objects. In short, personal objects are easily processed (N2) and boosted when accessing to personal semantic meaning (P3).

This pattern of source dynamics was also observed in the effective connectivity model. Our results suggest that, in a first instance, pCC, paraHC and PC are highly coupled when accessing and recognizing non-personal (as compared to personal) objects based on perceptual characteristics. But later in time, personal objects take advantage accessing to semantic self-knowledge, this being minimal (or absent) in non-personal objects. This finding may be revealing a continuum in the integration of external and internal self-specific information. The posterior system seems therefore to be engaged in two transient stages: (a) automatic perceptually-based identification of external stimuli, and (b) memory integration of autobiographical content. In case that the recognized stimulus, even familiar, is related with personal content, such representation has a preferential access to personal objects based on a deep recollection of personal episodic/semantic context and affective meaning (self-knowledge). Shah et al. (2001) and Maddock (1999) also observed similar activation of pCC when retrieving emotional, high salient stimuli from episodic memory. The implication of paraHC, in conjunction with medial/lateral prefrontal cortices, lateral/medial temporal cortices -including hippocampus and paraHC- and posterior cingulate have been consistently observed in autobiographical memory processing (Cabeza and St Jacques 2007; Spreng et al. 2009; St Jacques et al. 2011). Less is known, however, on how these areas are coupled in a neural net. Our data reveal that the pCC is transferring information to PC synchronized in the theta band, particularly when processing non-personal objects. This would be likely linked to novelty and lower familiarity. Posteriorly, such activation ceases to non-personal objects, but continues to personal objects, likely to bring past knowledge to mind transiently during the task. The neural activity in the theta band has been associated to working memory and short-term memory, as well as to emotional arousal processes (Başar et al. 2008; Knyazev 2007; Neuner et al. 2014).

Taken together, in an early stage, ERP and connectivity results reveal an automatic processing of other's objects information, based on their general perceptual features, whose meaning is irrelevant for the participant. This contrasts with more sustained and facilitated processing of personal and relevant information. This supports the hypothesis that personal content has a prioritized access, with lower deployment of attentional resources to non-personal objects.

The Evaluation of Personal Meaning Requires Fronto-Parietal Connectivity

At later latency, personal objects elicited larger P3 amplitude compared to non-personal objects at central sites, as an index of higher activation of semantic knowledge about the objects being recognized, allocating more attentional resources. The stronger P3 effect to personal objects may encompass the effective connectivity revealing higher level of coupling in posterior areas along with aCC and oPFC. The increase of the P3 modulation to self-related information has been consistently observed in the ERP literature (for a review, Knyazev 2013). For instance, Gray et al. (2004) noticed a larger P3 amplitude to autobiographical self-related and self-relevant stimuli (one's own first name). These authors concluded that self-relevant stimuli receive preferential access to attentional resources, particularly when these stimuli enclose emotional content. As reported by Su et al. (2010) and Tacikowski and Nowicka (2010), a P3 component around 350–500 ms time-window may index the evaluation of salient or motivationally relevant information. Xu et al. (2017) also observed larger P3 amplitude to highly important self-related content than for minimally important. In this line, our results in this latency may indicate that personal objects elicit higher-order attentional resources based on their salient categorization and their relative personal meaning as owned objects, since the P3 amplitude showed the largest amplitude to personal objects with high self-relevance. This was not observed in the non-personal objects. Such effect of relevance was revealed transiently in a constrained time-window at frontal electrodes (F3 and F4). This effect has been attributed to the meaningfulness of self-relevant information (Johnson 1986) and, in turn, the relevance attached to an object may be favoring attentional efforts to categorize and recognize the current object. Interestingly, the P3 has been associated to the semantic processing of the stimulus. For instance, Paller et al. (2003) observed that those faces that were supplemented with additional semantic information about the person elicited a greater positivity in centro-parietal electrodes in the 300–600 ms time window.

These ERP results were complemented by the effective connectivity around this latency. From 400 ms to the motor response, both pCC/PC and paraHC seem to be strongly coupled with aCC. It is likely this link is more dedicated in the personal meaning evaluation of the owned objects compared to non-personal objects, which may explain the increase of P3 amplitude. It has been shown that in explicit retrieval from autobiographical memory, an increase of PC activity may play a role in discriminating personal experience associated to the own objects from other visual representations lacking past experience (Andreasen et al. 1995; Lou et al. 2004). On the other hand, pCC is an associative cortex allowing the brain to integrate both external and self-generated information (Cavanna and Trimble 2006). Further, pCC activity also may be involved in cognitive process related to personal experiences. For instance, Lou et al. (2004) observed a functional connectivity between dmPFC and pCC/PC regions when subjects had to categorize self-related adjectives, concluding that this anterior–posterior network may be a central structure in self-representation. We may argue that the different pattern of activity in the posterior hub may be expected by virtue of recollecting to a greater or lesser extent from past experience linked to owned objects. Personal objects are virtually associated with a conscious experience of remembering semantic self-knowledge. For instance, a personal laptop or our own smartphone are linked to past and intimate experiences of use or affective feelings accrued across time, absent for other objects.

Neural integration within this widely distributed net seems to be governed through low frequency oscillations that encompassing the precise neural activations in memory-related processes (Buzsaki and Draguhn 2004; Düzel et al. 2010; Neuner et al. 2014). We have observed that the personal objects, as opposed to non-personal objects, elicited an increased synchronization between the pCC and the PC in the theta band, as well as and increased coupling between paraHC and the pCC at this frequency (450–500 ms). The pCC is thereafter synchronized in the time-window 500–600 ms to aCC in the theta band to personal objects in a larger extent than non-personal objects. Finally, in an earlier (400–500 ms) time-window, the anterior hub is effectively connected with the posterior hub by means of the aCC. While this connection was significantly larger for personal objects (particularly aCC to PC), the connection aCC to pCC did not survive the statistical threshold in the other condition. Interestingly, personal objects elicited a long-lasting ERD in the alpha band from PC to subcallosal (ventral aCC), likely as a reflection of top-down cognitive control depending on task demands. Previous studies have revealed that alpha suppression or desynchronization is related to selective attention. Particularly, Klimesch (2012) argued that alpha-band oscillations relate to suppression (inhibition, ERS) and selection (timing, ERD), enabling controlled knowledge access and retrieval. In this respect, our data reveals that PC and ventral aCC may be largely engaged in selective attention when retrieving integrated semantic self-knowledge, blocking other information processing outside the attentional focus. In fact, the global pattern of connectivity at their respective frequency bands between anterior and posterior areas may be revealing an attentional system preferentially focused on keeping relevant self-meaning content of owned objects and dealing with self-control processing, to better address task demands.

In sum, electrophysiological results suggest the existence of a highly-integrated network activated when a person has to identify and evaluate objects based on their personal significance, contrasting with other, non-personal but similar objects. Moreover, the pattern of activation seems to be gradual, being activated to lower levels if there is not attached self-knowledge content and to higher levels if the object conveys high self-relevance.

Limitations of the Present Study

A limitation of this study is that familiarity was not explicitly manipulated. Our data, for instance, reveal a decrease of the N2 that may be explained by greater exposure to personal objects. The P3 results, however, cannot be interpreted in this way, as it has been associated to personal meaning extracted from the stimulus being recognized (e.g., in face processing, Bruce and Young 1986). In this line, the connectivity pattern in later latencies (400–500 ms) evidenced that personal objects elicited a significantly higher coupling in PC, pCC and paraHC, along with the aCC, revealing the preferential access to the *self knowledge-based familiarity* beyond perceptually-based familiarity (Cloutier et al. 2011). Several studies have observed that familiarity with an object (self, familiar other, rest) engages common activation of the pCC (Legrand and Ruby 2009; Qin and Northoff 2011). However, its activity increases when evaluating and judging self-related objects and decreases to familiar other and rest conditions. It is though that pCC may be modulated by anterior areas such as mPFC or aCC (Qin and Northoff 2011). Strauman et al. (2013) observed that in two different conditions (promotion goals vs prevention goals), the pCC appeared activated in both, but to a greater extent in the self-relevant condition (promotion goals: hopes and aspirations). We found however that the pCC as a main driver in the parietal network, being involved in both kinds of objects, becomes more engaged in personal objects as a reflection of subjective experience of self (mineness) (Legrand and Ruby 2009; Qin and Northoff 2011).

Previous studies that ruled out this confound have used the paradigm of mere ownership. Thus, they eliminate any semantic self-knowledge associated to the experimental objects. Although that paradigm empirically addresses the aspect of self-relatedness, it has not much to say about the extensive and affective self-knowledge linked to the objects. In addition, our procedure addresses the structure of the self more ecologically.

Concluding Remarks

The present study, through an innovative, multiple-step procedure, combines conventional ERP analysis with brain dynamics to provide a more comprehensive view on the neurocognitive basis of such a complex brain function as is self-related information processing, i.e., the self. We have proved an early access/retrieval to personal knowledge of our possessions that primes or gains access to higher-order cognitive resources. Importantly, the connectivity between the analysed brain areas substantiates the temporal evolution of the activation of a fronto-parietal network, starting at early latencies to the response time. This study has proved for the fist time that personal belongings have a privileged status in our mind/brain, yet more when they encompass highly personal meaning, based on the semantic and affective content available in autobiographical memory. In particular, the processing of personal objects relates to an enhanced coupling of brain areas that represent the self that in turn enhance integration of perception and memory in contrast to non-personal objects.

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