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Attractiveness and affordance shape tools neural coding: Insight from ERPs

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A B S T R A C T

The relation between attractiveness and motor affordance is a key topic in design and has not yet been investigated electrophysiologically. In this respect, action affordance and attractiveness represent two crucial dimensions in object processing (specifically for tools). In light of this evidence, Event Related Potentials (ERPs) enabled us to gain new insights into the time course of the interaction between these two dimensions during an explicit tool evaluation task.

Behaviorally, tools that were judged as high affording and high attractive yielded faster response times than those judged as low affording and low attractive.

The ERP results showed that early processes related to sensory gating and feature extraction (N100) were sensitive to both affordance and attractiveness; the P200 was dominated by affordance, indexing a facilitated access to motor action representation. The N300, P300 and the Late Positive Potential (LPP) showed enhanced responses for highly affording/attractive tools, reflecting the interconnection between attractiveness and affordance. Later responses were entirely affected by attractiveness, suggesting additional affective responses evoked by desirable tools.

We are showing that things that are perceived as more functional and attractive have a privileged neural activation in the time course of tool evaluation, for the first time.

1. Introduction

In everyday life we choose to purchase and use particular objects, rather than others, on the basis of our subjective preference. This preference emerges by considering both esthetic and functional attributes. Behavioral studies from industrial designers showed shorter times in the interaction with objects judged as attractive (Norman, 2003; Tractinsky, 1997; Tractinsky et al., 2000). Thus, some insights into this topic come from the intriguing hypothesis “attractive things work better”. This suggests that an esthetically pleasing appearance enhances our ability to detect the action possibilities (motor affordance) of artifacts (Norman, 2002, 2004). As far as we know, attractiveness and motor affordance have always been investigated separately and there is a substantial lack of psychophysiological studies investigating this important interaction in the processing of usable tools.

Therefore the present study shines light on the neural correlates that reflect the interaction between motor affordance and attractiveness. If it is true that the esthetic value allows users to enhance the detection of action possibilities and, consequently, the detection of motor affordance (Xenakis and Arnellos, 2013), then it becomes crucial to explore the different cognitive operations involved in artifact evaluation as a function of both esthetic and affordance.

Brain imaging research on neuroesthetic shows that the core neural networks underlying pleasure evoked by beauty are likely to engage the same neural structures that mediate emotions, and, in particular, the reward systems (Cela-Conde et al., 2004; Ishizu and Zeki, 2011; Kawabata and Zeki, 2004; Marzi and Viggiano, 2010; Vartanian and Goel, 2004; Wiesmann and Ishiai, 2008; Chatterjee et al., 2009). Thus, it has been found that the esthetic experience involves a widely distributed circuit with greater activation for beautiful stimuli in anterior cingulate gyrus, dorsolateral and medial frontal cortices (Berridge and Kringelbach, 2008; Breiter et al., 2001; Di Dio et al., 2011; Kirk et al., 2009).

Furthermore, the temporal aspects, as assessed by magnetoencephalographic (Cela-Conde et al., 2004; Munar et al., 2012) and event related potential (ERP) (Höfel et al., 2007; Jacobsen, and Höfel, 2003) studies are characterized by two-stage processing of beauty. Around 300–400 ms, the neural activity is already sensitive to subjective evaluation (Höfel et al., 2007; Jacobsen and Höfel, 2003) and a greater activation of dorsolateral prefrontal cortex was found when subjects rated the stimuli as beautiful, reflecting a fast impression formation that influenced attention, perception and response selection (Höfel et al., 2007; Jacobsen and Höfel, 2003; Cela-Conde et al., 2004, 2011). Later on, from 400 to 1000 ms, esthetic appreciation is indexed by an enhanced positivity for stimuli which are perceived as beautiful compared to stimuli which are perceived as ugly (de Tommaso et al.,

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2008; Höfel et al., 2007; Jacobsen and Höfel, 2003). This ERP pattern has been related to the Late Positive Potential (LPP) reflecting the affective and emotional processes which are an integral part of our esthetical experience for abstract patterns (Höfel et al., 2007; Jacobsen and Höfel, 2003), artistic paintings (de Tommaso et al., 2008) or highly attractive faces (Marzi and Viggiano, 2010). It is noteworthy to underlie that the neural responses evoked by attractive tools have yet to be explored. Regarding the processing of tools, a further important aspect to consider is affordance. The notion of affordance, introduced by Gibson (1986), suggests that the sight of an object implies the immediate and automatic selection of its intrinsic features that facilitate our interaction with it. Affordance is described as a "direct link between the perceived visual properties of an object and an action that may be performed with it" (Humphreys and Riddoch, 2001). Hence, affordance, considered as the range of action possibilities afforded by the visual perception of an object, is a very useful cognitive tool for linking perception with action (Norman, 1990). Behavioral (Borghi, 2004; Costantini et al., 2010, 2013; Tucker and Ellis, 1998, 2001; Vingerhoets et al., 2009, Randerath et al., 2013), neuroimaging (Chao, and Martin, 2000; Grèzes et al., 2003; Vingerhoets, 2008), neuropsychological (Johnson-Frey, 2004) and electrophysiological (Proverbio et al., 2007, 2011) studies agree that the vision of a manipulable object implies an automatic access to the motor programs to act. In particular, the observation of manipulable tools activates the fronto-parietal network and the left premotor cortex possibly indexing an automatic activation of motor schemata related to hand and arm movements (Cardellicchio et al., 2011; Creem-Regehr and Lee, 2005; Grafton et al., 1997; Jeannerod et al., 1995; Proverbio et al., 2013, see Castiello, 2005). Several studies show that some cerebral areas (i.e. posterior parietal and premotor cortex, Cardellicchio et al., 2011) are specialized in conveying information associated with the motor affordance of a tool or manipulable object; these areas respond to tools without the performance of any action. Moreover, it is important to point out that the motor coding for using an object is mainly extracted from the observation of its shape (Proverbio et al., 2007). Viewing tools automatically activates the mental representations associated with their manipulation (Proverbio et al., 2007, 2011, 2013; Cardellicchio et al., 2011, Castiello, 2005), and this neural activation is different for graspable objects, and depends on the different motoric properties (Creem-Regehr and Lee, 2005; Proverbio et al., 2012, 2013). It is likely that within the tool category the manipulability-related differences differently modulate the neural activity. Furthermore, neuropsychological studies (Johnson-Frey, 2005; see also Maravita and Iriki, 2004) support the idea that manipulable objects might be part of a plastic neural representation of the body.

Electrophysiological studies (Proverbio et al., 2007, 2011) suggested two stages of affordance coding during the observation of manipulable objects. Within 250 ms an anterior negativity, mainly distributed on the left premotor areas, reflects the early activation of the motor representations linked to the object use. Later on (550–600 ms), a larger centro-parietal P300 in response to tools versus non-manipulable objects reflects the preferential orienting of attention to objects providing motor affordance (Proverbio et al., 2007, 2011).

In light of these findings, our aim was to explore whether and when tool evaluation process might be affected by both perceived attractiveness and action affordance. The concept of attractiveness for tools, instead of esthetic or beauty, is used here in order to underline the subjective emotional attraction and desirability for tools. We use the concept of "action affordance" (Proverbio et al., 2011) which means the subjective perceived degree of motoric associations related to the knowledge of learned motor representations that enable the correct use of familiar tools (Valyear et al., 2007). In this vein, the evaluation of "high affording" is given when subjects immediately and automatically are able to evoke the motor responses associated to the visually presented tools. Specifically, the major goal of our study was to pinpoint the neural correlates of the interaction between these two dimensions.

For these purposes ERPs were employed to assess the temporal dynamics of the interaction between attractiveness and action affordance. Images of man-made usable tools (matched for size, luminance, visual complexity, manipulability and familiarity) were presented and participants were instructed to evaluate them for both action affordance (high or low) and attractiveness (high or low). This particular procedure enabled us to tap the intrinsic relation between affordance and attractiveness because ERP responses to each presented tool indexed both judgments (e.g. tools judged as highly affording and highly attractive).

The starting questions were the following: i) which processing stages are affected by perceived action affordance or attractiveness or both?; ii) when do attractiveness and affordance begin to interact during the time course of visual tool explicit evaluation processes?

It is important to clarify that the focus of this work was to gain further insights into the neural and cognitive processes that subserve the explicit evaluation of every-day tools. The understanding of which physical features influence the evaluation processes is beyond our aim and is a topic for further study.

Early and late ERP components were considered in order to characterize the sequence of neural events from early attentional mechanisms that foster perceptual feature extraction (visual N100 in anterior and posterior areas), functional and motor representations processing (P200, N300), allocation of attention (P300) up to later affective processes related to esthetic evaluation (LPP and Late frontal positivity, LFP).

Given the importance of both attractiveness and action affordance in our preferences for every-day objects, we expected to find different neural responses evoked by tools that are subjectively evaluated as evoking a strong representation of the associated motor interaction (high affording) and also were very attractive compared to low affording and low attractive tools. Specifically, by considering both tools processing studies and the few electrophysiological studies that investigated affordance and attractiveness. It is likely that high affording/high attractive tools evaluation might exert additive effects on the neural activity. Hence, we hypothesized that high affording/high attractive tools might elicit an amplitude enhancement of the P200, indexing the access to the object representation system (Amsel et al., in press; Luck and Hillyard, 1994; Phillips and Takeda, 2009; Schendan and Lucia, 2010) and of the fronto-central N300, indexing conceptual processing (Schendan and Kutas, 2007), motor representations processing (Proverbio et al., 2011; Petit et al., 2006) and esthetic appreciation process (Jacobsen and Höfel, 2003). Moreover, the evaluation of high affording/high attractive tools may enhance the P300 component that represents an attentional updating process (Polich, 2007) and has been shown to be sensitive to positive arousing stimuli (DelPlanque et al., 2004, 2006; De Tommaso et al., 2008). Taking into account that several studies related the LPP to intentional (Cacioppo et al., 1996; Crites and Cacioppo, 1996; Cunningham et al., 2005) and esthetic evaluative processes (Jacobsen and Höfel, 2003; Höfel et al., 2007) we can expect that LPP is enhanced for high attractive tools. In addition, incongruent judgments for the same tools, i.e. low affording/high attractive, might also elicit some specific neural activation during attentional and perceptual processes related to incongruence. In this sense, incongruence may yield a more effortful attentional and structural processing, as reflected by larger visual N100 in anterior and posterior areas (Vogel and Luck, 2000; Paz-Caballero et al., 2011; Tanaka et al., 1999; Schendan and Lucia, 2010), while a facilitation in processing might be found with congruent high affording/high attractive tools. Specifically, a larger modulation of the N100 may characterize the incongruent stimuli because of pre-attentive mechanisms that guide the feature extraction in order to detect task-relevant stimuli features. This hypothesis may be supported by visual search studies (Luck and Hillyard, 1995) that suggested that the visual N100, which may peak earlier in frontal compared to posterior sites (Ciesielski and French, 1989), was evident only when a discrimination was required (Mangun and Hillyard, 1991). Furthermore the visual N100 has been shown to be functionally independent from other visual evoked potentials, such as the P100

(Spitz et al., 1986; Luck and Hillyard, 1995). Specifically, the P100 typically peaks around 80–130 ms over occipital areas and is sensitive to spatial location in the visual field (Mangun, 1995), luminance (Cant et al., 1978), shape and color (Luck et al., 1995). Differently, the visual N100 has an early anterior (around 140 ms) and a later posterior deflection (temporo-occipital sites around 190 ms) and, although sensitive to low level attributes (i.e. spatial frequency, Carretié et al., 2007), is mainly related to the capacity of the stimuli to attract and maintain the participant's attention in extracting the higher-order features of the stimuli (Carretie et al., 2003).

Overall, high affording tools are expected to automatically activate the representations of motor schemata, while high attractive tools might enhance components related to emotional–affective evaluation.

Finally, we predict that tools endowed with both high affordance and attractiveness should evoke specific amplitude patterns at different stages, providing evidence for a specific and facilitated processing.

2. Methods

2.1. Participants

Fourteen healthy right-handed Italian students (8 females, mean age of 22.36, SD = 2.61) with normal or corrected-to-normal vision and without history of neurological or psychiatric disorders participated in the experiment. None of the participants had received professional training in the fine arts, industrial design and architecture or had participated in a similar experiment before. Moreover, no participants had particular expertise with the presented tools but all had normal, “domestic” – non professional – skills to use the presented tools. All participants were right-handed as determined by the Italian version of the Edinburgh Handedness Inventory (Viggiano et al., 2001).

Two participants were excluded because they had not enough artifact-free trials during ERP analysis in at least one relevant condition leaving a final sample of twelve participants (6 females, mean age of 22.00 SD = 2.65).

2.2. Stimuli

The stimulus set consisted of 400 colored pictures of everyday tools including instruments associated with specific motor acts (e.g., scissors, spoons, pitcher), these were selected from a previous pilot study. The tools included common house-hold utensils and office tools and objects related to specific professional skills were excluded.

Stimuli were equated in terms of size, central alignment of the stimuli within the image. Luminance of each individual stimulus was equated to match the overall mean luminance of all objects by employing gradation curve adjustments in Adobe Photoshop® 7.0.

The color was maintained to provide a more ecological representation of tools and because the people's esthetic preferences are related also to the color of objects (Palmer and Schloss, 2010). All pictures were shown on a white background. All stimuli were centrally displayed and inscribed into a square of 280 × 280 pixels in order to equate the maximal extension corresponding to a picture size on the screen of about 10.3 ×10.3 cm. At a viewing distance of about 90 cm, the visual angle subtended 6.5°. Fig. 1 shows some every-day tools used in the experiment.

In the previous pilot study, 860 everyday familiar objects were randomly presented one by one on a screen to 15 subjects (8 female; age range: 20–40 years), which were right-handed and uneducated in fine arts, industrial design and architecture. These subjects were instructed to judge each stimuli on a 5 point Likert scale (1 = very low in the examined dimension, 5 = very high in the examined dimension) for the following variables:

1) *Visual complexity* that was defined as “the amount of colors, details and intricacy of lines and edges in the picture” (Snodgrass and Vanderwart, 1980).
2) *Familiarity* that was defined as “how frequently you come in contact with the stimulus, both in a direct way (running into a real exemplar of the object) and in a mediated way (seeing it represented in the media, as newspapers, TV or others)” (Snodgrass and Vanderwart, 1980).

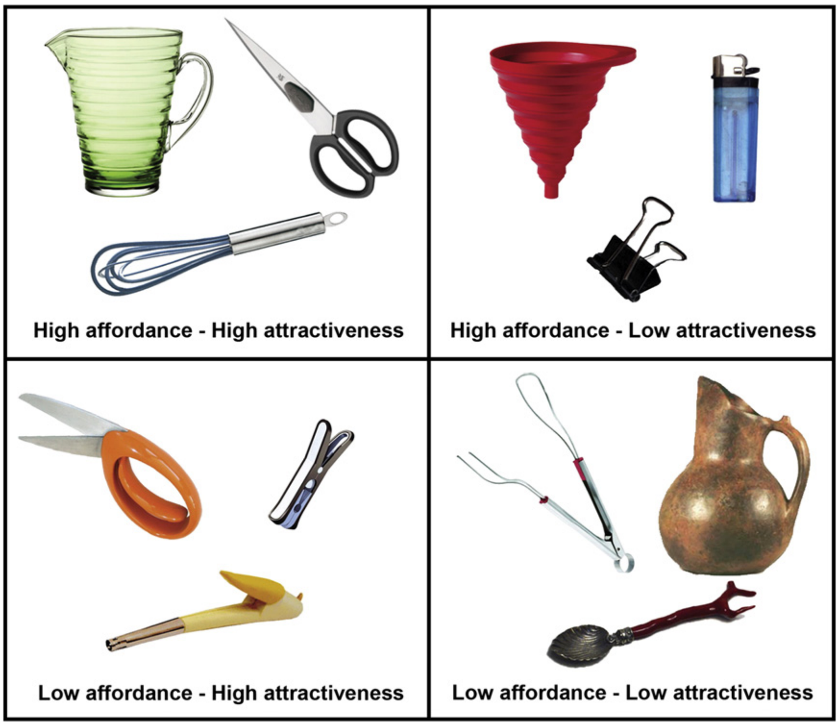

Fig. 1. Example of the images of tools presented that vary as a function of affordance and attractiveness.

3) *Manipulability* that was defined as “the extent to which the objects are capable of being grasped and manipulated by one hand” (Grezes and Decety, 2002).
4) *Action affordance* that was defined as “the degree to which the presented object evoked a motor association (Proverbio et al., 2011) considering also the degree to which the shape of the object implies how it should be unambiguously used” (Wolk et al., 2005).
5) *Attractiveness* that was defined as “how an object is considered attractive, desirable and esthetically pleasing” (Marzi and Viggiano, 2010).

Based on the pilot study's results, 400 tool pictures were selected considering: 1) the manipulability score above the median (m = 2.6; SD = 0.85); 2) affordance and subjective attractiveness judgments above or under the 75th (affordance = 3.62, SD = 0.52; both esthetic judgment = 2.80, SD = 0.55) and 25th (affordance = 3, SD = 0.52; esthetic judgment = 2, SD = 0.55) percentiles respectively; 3) both familiarity and visual complexity in the range between 2 and 4. The stimuli used were selected in order to hold both familiarity and visual complexity constant across the different ratings. Furthermore the stimuli of the four classes were also matched in shape to ensure that, for example, long, narrow and/or small objects were not concentrated specifically in one category.

This procedure allowed us to obtain homogenous subsets of stimuli with high and low ratings for the studied dimensions. Hence for the ERP study we made sure to have the same number of stimuli for the different ratings. A correlation analysis was performed to explore whether affordance and esthetic judgments were related. Interestingly, affordance and esthetic judgments were correlated ($r = .50$, $p < .001$), according to previous reports (Chawda et al., 2005).

2.3. Procedure

Subjects were seated in front of a computer screen in a dimly lit room. The whole experiment consisted of 10 blocks of 40 randomly presented stimuli (total = 400 tools). Each trial began with a black fixation cross against a light gray background (1000 ms) followed by a random (300–600 ms) interstimulus interval (ISI). The stimulus was displayed for 1000 ms and followed by two different response displays (one for attractiveness and the other for affordance). Participants were requested to judge whether the presented tools were characterized by “high” or “low” action affordance (Proverbio et al., 2011; Wolk et al., 2005), and “high” or “low” attractiveness (Marzi and Viggiano, 2010) by pressing one of two buttons. In half of the blocks (5) participants were required to judge first affordance and then attractiveness, whereas in the other half (5) the order of judgment was inverted and subjects had to evaluate attractiveness before affordance. The order of block presentation was randomized across participants. Furthermore, the left or right hand was used to respond and was counterbalanced across subjects and within the judgments (affordance and attractiveness).

The entire experiment lasted about 1 h and 15 min, including electrode placement and instructions. Prior to the experiment participants were acquainted with the task in a training session. The stimuli used in the training were different from those of the experiment.

Overall, during the EEG recording each subject classified the tools according to four combinations: 1) high affording/high attractive, 2) high affording/low attractive, 3) low affording/high attractive, and 4) low affording/low attractive. The analysis was performed considering the subjective ratings of each participant because we were interested to connect the electrophysiological activity with the subjective explicit evaluation of both affordance and attractiveness.

2.4. Electrophysiological recording

The electroencephalogram (EEG) was continuously recorded trough a Neuroscan NuAmp amplifier from 28 Ag/AgCl electrodes (F7, F3, Fz, F4, F8, FT7, FC3, FCz, FC4, FT8, T3, C3, Cz, C4, T4, TP7, CP3, CPz, Cp4, TP8, T5, P3, Pz, P4, T6, O1, Oz, O2). The electrodes location was based on an expanded version of the international 10–20 electrode placement system. A linked-mastoides (left and right) reference was used. Vertical and horizontal electro-oculographic activity (EOG) was recorded with additional electrodes located above and below the left eye and outside the outer canthi of both eyes. For all electrodes impedance was reduced to less than 5 kΩ. Electrical activity was amplified with a bandpass from 0.01 to 100 Hz and a sampling rate of 1000 Hz. In offline analysis the data were epoched into single sweep recordings from 200 ms before stimuli onset to 1000 ms after stimuli. Drifts were corrected by applying a high pass filter of 0.01 Hz with a zero phase shift. Moreover, each epoch was baseline corrected using the signal during 200 ms that preceded the onset of the stimulus. All epochs with ocular artifacts greater than 60 μV were automatically rejected. Moreover epochs were visually scanned to find further artifacts (EMG artifact and alpha wave intrusions). ERPs were then averaged separately for each channel and experimental condition, and low-pass filtered at 30 Hz (24 dB cut-off). ERP responses were triggered by stimulus onset and therefore were not contaminated by the motor response that was performed after the recording epoch was over.

The EEG of each subject was averaged separately for all the combinations of stimulus type and the mean number of trials for each category was: high affording/high attractive = 85.33 (SD = 9.99), high affording/low attractive = 86.92 (SD = 14.06), low affording/high attractive = 78.00 (SD = 15.90), low affording/low attractive = 80.92 (SD = 18.03).

The ERP analyses were conducted on the mean amplitude values for specific sets of electrodes within predefined time windows: 90–180 ms (fronto-central N100), 180–260 ms (posterior N100), 180–260 ms (fronto-central P200), 300–500 ms (fronto-central N300 and centro-parietal P300), 500–750 (Late Positive Potential — LPP) and 750–950 (Late Frontal Positivity). These time windows were selected on the basis of visual inspection of grand average amplitudes (Fig. 2), scalp topographies (Fig. 3), and based on previous ERP studies on visual attention (N100 — Vogel and Luck, 2000; Carretie et al., 2003) and object recognition (P200 — Paz-Caballero et al., 2011; Antal et al., 2001; Schendan and Lucia, 2009), affordance (P200, N300 — Petit et al., 2006; Proverbio et al., 2007, 2011), and esthetics (N300, P300, LPP and Late Frontal Positivity — de Tommaso et al., 2008; Jacobsen and Höfel, 2003; Höfel et al., 2007). The electrodes included in the analysis were: F3, FZ, F4, FC3, FCZ, FC4, C3, CZ, C4, CP3, CPZ, CP4, P3, PZ, P4, T5, T6. Moreover, we conducted further analysis on the P100 component (between 90 and 180 ms) to control for a possible effect of visual sensory processing.

2.5. Statistical analyses

The analyses were performed by considering the subjective ratings of each participant by using repeated measures ANOVAs.

The proportion of judgments for each category was compared by means of the chi-square test.

Reaction times (RTs) were recorded from onset of the visual instruction on which type of judgment was required (affordance and attractiveness), this was presented on the monitor and participants had to press the appropriate response button (one for “high” and one for “low” judgments). RTs were analyzed with a repeated measure ANOVA factoring: Type of judgment (indicating the type of response requested: Affordance and Attractiveness), Affordance at two levels (High and Low) and Attractiveness at two levels (High and Low).

ERP analyses were conducted on mean amplitude values by using ANOVAs with Affordance at two levels (High, Low), Attractiveness at two levels (High, Low), and Side at three levels (Left/Middle/Right). The sites varied depending on the analyzed component. The fronto-central N100, the fronto-central P200 and the Late Frontal Positivity (LFP), were separately analyzed on frontal, centro-frontal and central electrode clusters (F, Fc and C); the LPP was analyzed by considering

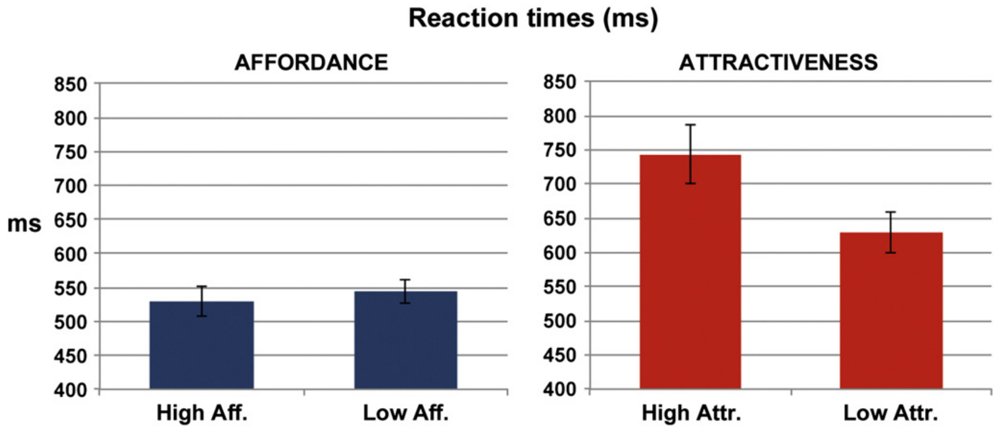

Fig. 2. Reaction Times (RTs) graphic in which factors are collapsed so that the factors affordance (low/high) and attractiveness (low/high) are visible.

also centro-parietal and parietal electrodes (CP and P). The fronto-central N300 was separately explored on frontal and centro-frontal sites (F, and Fc) while the centro-parietal P300 on central, centro-parietal and parietal sites (C, CP and P). Hence each ANOVA was computed on three electrodes for each site considered (i.e. on frontal areas the analysis was performed on F3, Fz and F4 with the factor Side at three levels: Left/Middle/Right). The posterior N100 was analyzed on occipital (Side: O1 and O2), temporal (Side: T5 and T6) and parietal (Side: P3 and P4) sites and the P100 on temporal (Side: T5 and T6) and occipital sites (Side: O1 and O2).

On the ERP components where both the main effects of Affordance and Attractiveness were significant we ran further ANOVAs considering

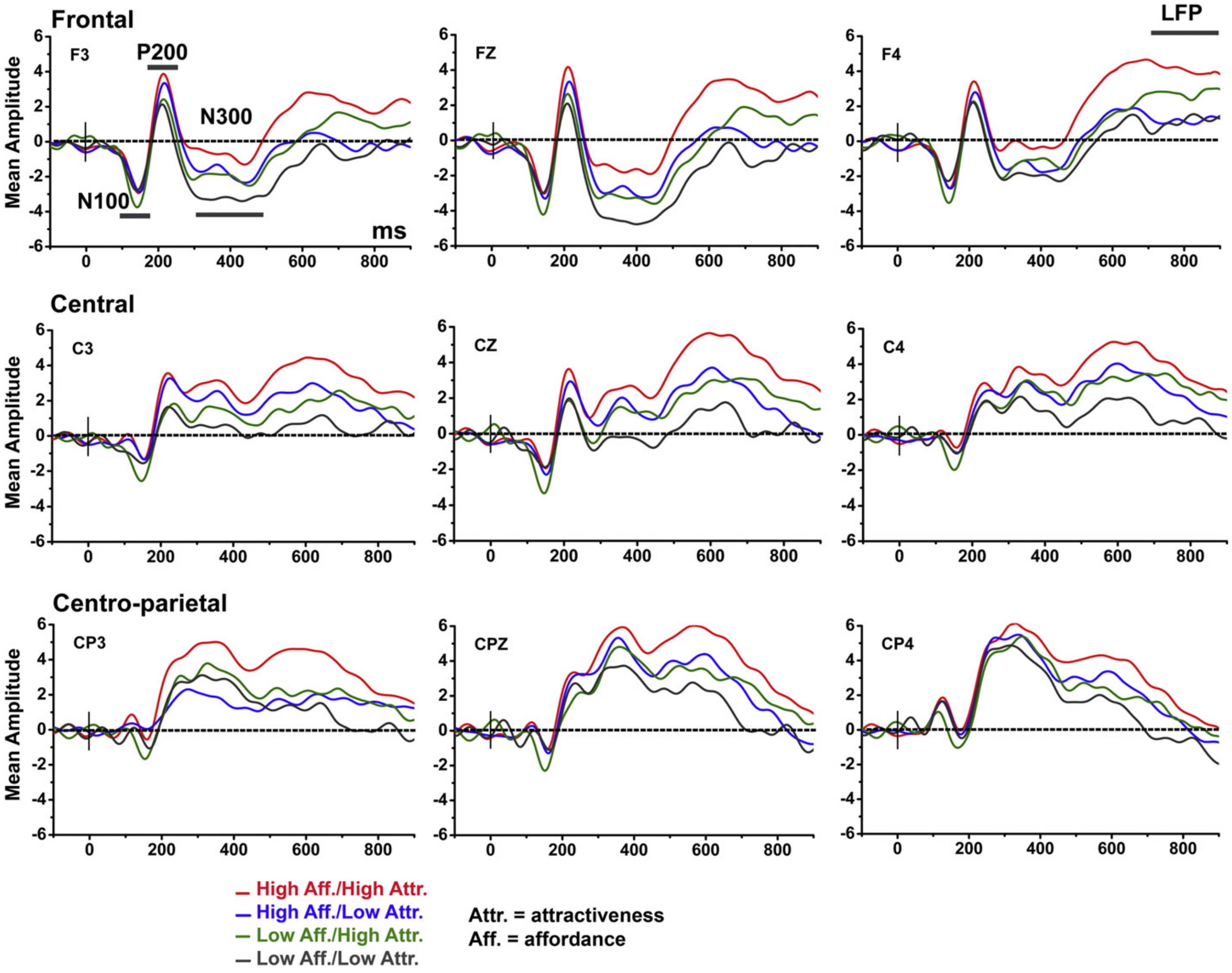

Fig. 3. Grand-averaged ERPs responses to the evaluation of both (high and low) affordance and attractiveness for frontal, central and centro-parietal sites.

the same locations and factoring the same Side as for the original analysis. In these additional ANOVAs the factor Condition was at four levels: 1) high affording/high attractive, 2) high affording/low attractive, 3) low affording/high attractive, 4) low affording/low attractive. These analyses were carried out to better explore the differences between high affording/high attractive and low affording/low attractive tools.

In order to correct violations of the sphericity assumption in multiple testing the Greenhouse–Geisser correction was applied for all ANOVAs and adjusted degrees of freedom rounded to the nearest whole number are reported. All the significant main effects and interactions were reported considering also the effect size (eta squared η^2). Post hoc tests included additional ANOVAs, corrected with Greenhouse–Geisser correction, or paired t-tests, corrected with Bonferroni for multiple comparisons.

3. Results

3.1. Behavioral data

Table 1 shows proportion of judgments for the four categories. The chi-square conducted on proportion of judgments for each category revealed no significant differences (all $p_s > .05$).

As to RTs, the ANOVA showed the main effects of Affordance, $F(1, 11) = 4.82$, $p < .05$, $\eta^2 = .32$, and Attractiveness, $F(1, 11) = 6.44$, $p < .028$, $\eta^2 = .37$, with faster responses for high affording compared to low affording and low attractive compared to high attractive tools. The main effects were further specified by the two-way interactions: Type of judgment × Affordance, $F(1, 11) = 10.65$, $p < .008$, $\eta^2 = .49$, Type of judgment × Attractiveness, $F(1, 11) = 4.96$, $p < .048$, $\eta^2 = .31$, Affordance × Attractiveness, $F(1, 11) = 11.13$, $p < .007$, $\eta^2 = .50$, and the three-way interaction Type of judgment × Affordance × Attractiveness, $F(1, 11) = 5.10$, $p < .045$, $\eta^2 = .32$. This interaction showed longer RTs in judging attractiveness for low affording/high attractive tools compared to all other conditions (vs. high affording/high attractive: $p < .004$; vs. high affording/low attractive: $p < .007$; vs. low affording/low attractive: $p < .008$), see Table 1 and Fig. 2.

3.2. Electrophysiological data

The ERPs grand averages are shown in Figs. 3 and 4 for the following conditions: high affording/high attractive, high affording/low attractive, low affording/high attractive, low affording/low attractive. Moreover, Figs. 5 and 6 show ERPs to tools judged low versus highly affordable (independent of attractiveness), and low versus highly attractive (independent of affordability). Moreover, Table 2 summarizes the ERP results of the ANOVAs.

3.2.1. Fronto-central N100 (peak around 155 ms)

This component was modulated by the main effect of Affordance, [on frontal sites: $F(1, 11) = 7.37$, $p < .02$, $\eta^2 = .40$; on fronto-central sites: $F(1, 11) = 9.31$, $p < .01$, $\eta^2 = .46$; and on central sites: $F(1, 11) = 10.62$, $p = .008$, $\eta^2 = .49$], further qualified by the significant interaction Affordance × Attractiveness [on frontal sites: $F(1, 11) = 5.87$, $p < .034$, $\eta^2 = .35$; on fronto-central sites: $F(1, 11) = 6.59$, $p < .026$, $\eta^2 = .38$; and on central sites: $F(1, 11) = 4.45$, only close to significance, $p = .06$, $\eta^2 = .29$]. Specifically, attractiveness evaluation influenced the N100 across all the anterior sites with high attractive tools yielding larger amplitudes when they were simultaneously judged as low affording rather than high affording, [on frontal sites: $F(1, 11) = 15.1$, $p < .003$, $\eta^2 = .58$; on fronto-central sites: $F(1, 11) = 17.7$, $p < .001$, $\eta^2 = .62$; and on central sites: $F(1, 11) = 12.78$, $p < .004$, $\eta^2 = .54$]. No further comparisons were significant.

3.2.2. Posterior N100 (peak around 200 ms)

From 180 ms to 260 ms on parietal, temporal and occipital sites, very similar effects as those found in the previous time window emerged. The interaction Affordance × Side on occipital, $F(1, 11) = 8.09$, $p < .0015$, $\eta^2 = .40$, temporal, $F(1, 11) = 14.33$, $p < .003$, $\eta^2 = .57$, and parietal sites, $F(1, 11) = 6.59$, $p < .036$, $\eta^2 = .35$, showed on the left side a larger negativity for low affording with respect to high affording tools. Furthermore, on temporal sites the interaction Affordance × Attractiveness × Side, $F(1, 11) = 4.84$, $p < .05$, $\eta^2 = .31$, revealed that on T5 high attractive tools elicited larger N100 when they were simultaneously judged as low affording rather than high affording [$F(1, 11) = 12.98$, $p < .004$, $\eta^2 = .54$], see Figs. 4 and 6.

3.2.3. Fronto-central P200

Between 180 ms and 260 ms on anterior sites, the P200 (see Figs. 2 and 3) was modulated by Affordance [on fronto-central sites: $F(1, 11) = 5.53$, $p < .038$, $\eta^2 = .33$; central sites: $F(1, 11) = 6.18$, $p < .03$, $\eta^2 = .36$] with a left to midline lateralization [Affordance × Side: frontal sites: $F(1, 16) = 5.10$, $p < .028$, $\eta^2 = .32$; central sites: $F(2, 21) = 7.06$, $p < .005$, $\eta^2 = .39$]. Hence, high affording tools showed larger P200 amplitude compared to low affording tools in left (frontal: $F(1, 11) = 5.45$, $p < .04$, $\eta^2 = .33$; central: $F(1, 11) = 11.32$, $p < .006$, $\eta^2 = .51$) and midline electrodes (frontal sites: $F(1, 11) = 5.09$, $p < .045$, $\eta^2 = .32$; central sites: $F(1, 11) = 5.23$, $p < .043$, $\eta^2 = .32$).

3.2.4. Fronto-central N300

The significant effect of Affordance persisted on anterior regions [frontal sites: $F(1, 11) = 5.89$, $p < .033$, $\eta^2 = .35$; fronto-central sites: $F(1, 11) = 5.15$, $p < .044$, $\eta^2 = .32$] with a larger negative deflection for low affording compared to high affording tools, Fig. 2. The N300 was also influenced by Attractiveness [on frontal sites: $F(1, 11) = 13.22$, $p < .004$, $\eta^2 = .55$; fronto-central sites: $F(1, 11) = 5.88$, $p < .034$, $\eta^2 = 0.55$] with larger amplitudes for low attractive compared to high attractive tools. Thus, between 300 ms and 500 ms, the processing of both affordance and attractiveness exerts a mutual reinforcement, reflected by an enhanced N300 for tools evaluated as low affording/low attractive compared to those evaluated as high affording/high attractive [on frontal sites: $F(2, 18) = 6.98$, $p < .008$, $\eta^2 = .39$, (post-hoc: $p < .004$), and on fronto-central sites, $F(2, 25) = 5.10$, $p < .012$, $\eta^2 = .32$, (post-hoc: $p < .024$)].

3.2.5. P300

On central areas the main effect of Affordance, $F(1, 11) = 6.14$, $p < .0031$, $\eta^2 = 0.36$, was further specified by the significant interaction

Table 1
Mean and standard deviation (SD) for the proportion of judgments and RTs, for attractiveness and affordance, as a function of stimulus type: HAF–HAT = high affording/high attractive, HAF–LAT = high affording/low attractive, LAF–HAT = low affording/high attractive, LAF–LAT = low affording/low attractive.

	Judgments		RTs — type of judgment: affordance				RTs — type of judgment: attractiveness			
	Mean	(SD)	Mean	(SD)	Min	Max	Mean	(SD)	Min	Max
HAF/HAT	0.26	(0.03)	523.77	(195.48)	297.24	992.88	649.59	(267.89)	330.12	1212.11
HAF/LAT	0.27	(0.03)	534.9	(142.20)	350.78	911.84	647.42	(234.40)	335.39	1154.13
LAF/HAT	0.23	(0.04)	553.81	(169.34)	361.59	933.41	836.74	(391.01)	505.57	1745.87
LAF/LAT	0.24	(0.04)	534.81	(134.79)	339.41	818.57	610.14	(226.15)	364.31	1029.06

HAF: high affordance; HAT: high attractiveness; LAF: low affordance; LAT: low attractiveness

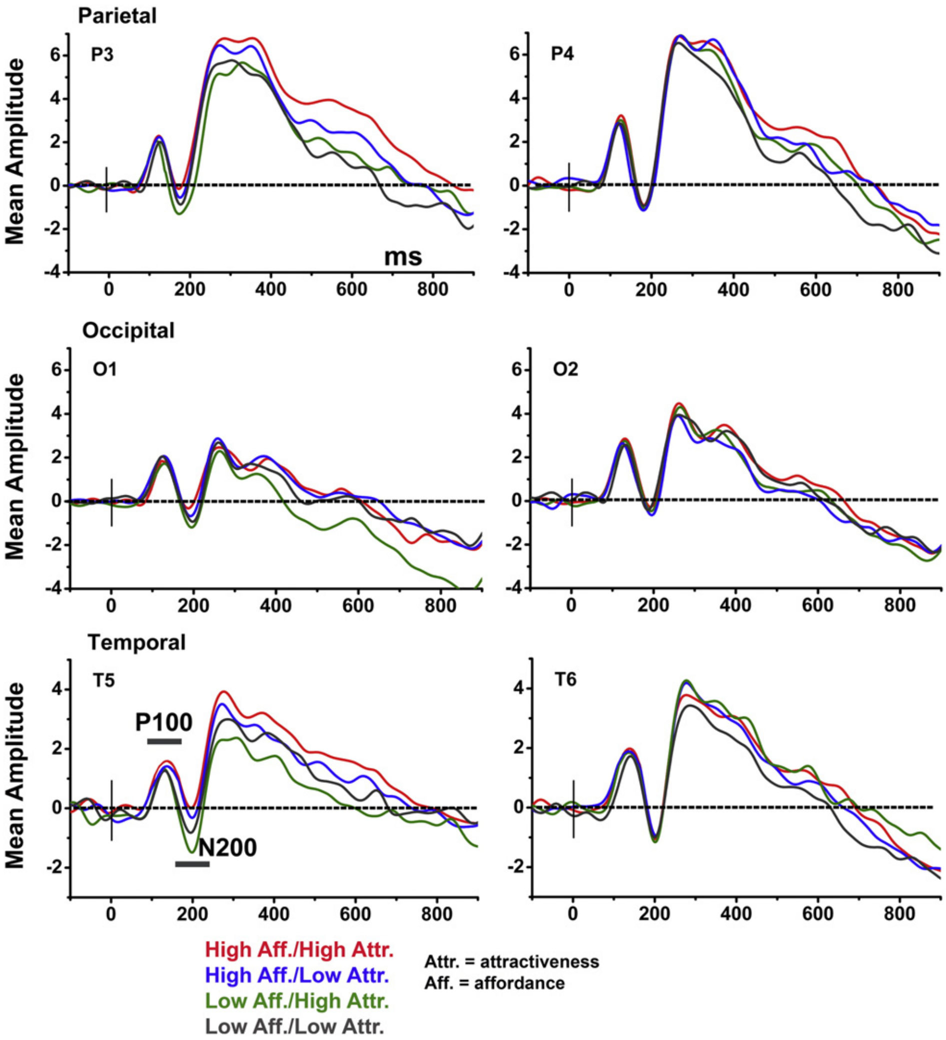

Fig. 4. Grand-averaged ERPs responses to the evaluation of both (high and low) affordance and attractiveness for parietal, temporal and occipital sites.

Affordance × Side, $F(2, 22) = 5.61$, $p < .011$, $\eta^2 = 0.34$, indicating on the left and midline sites (C3 and Cz) larger P300 amplitudes for high affording compared to low affording tools. Considering central sites also the interaction Attractiveness × Side, $F(2, 22) = 4.26$, $p < .028$, $\eta^2 = 0.28$, was significant, showing that in CZ, $F(1, 11) = 5.82$, $p < .034$, $\eta^2 = 0.35$, high attractive tools elicited a larger P300 compared to low attractive tools. Further analysis conducted on CZ revealed larger P300 amplitudes in the processing of high affording/high attractive compared to low affording/low attractive tools, [$F(3, 32) = 5.022$, $p < .007$, $\eta^2 = .31$, (post-hoc: $p < .009$)]. On centro-parietal sites only the main effect of Affordance, $F(1, 11) = 6.34$, $p < .003$, $\eta^2 = 0.37$, was significant whereas on parietal sites no significant main effect nor interactions emerged (all $p_s > .05$). Hence, similarly to the N300, the P300 was enhanced during the processing of attractive tools with perceived high action affordance.

3.2.6. Late positive potential (LPP)

The joined effects of affordance and attractiveness exerted their influence on tools evaluation also between 500 ms and 750 ms where a broad distributed positive potential expanded over anterior and posterior regions (see Fig. 3). High affording showed larger positive amplitude with respect to low affording tools, across all site clusters [Affordance: frontal: $F(1, 11) = 9.71$, $p < .010$, $\eta^2 = .47$; fronto-central:, $F(1, 11) = 11.84$, $p < .006$, $\eta^2 = .52$; central: $F(1, 11) = 12.33$, $p < .005$, $\eta^2 = .53$; centro-parietal: $F(1, 11) = 13.26$, $p < .004$, $\eta^2 = .55$; parietal: $F(1, 11) = 6.28$, $p < .029$, $\eta^2 = .36$]. Furthermore, high attractive tools produced enhanced neural activity prevalently on frontal and central sites [Attractiveness: frontal: $F(1, 11) = 8.49$, $p < .014$, $\eta^2 = .44$; fronto-central: $F(1, 11) = 6.55$, $p < .027$, $\eta^2 = .37$; central: $F(1, 11) = 12.33$, $p < .005$, $\eta^2 = .53$].

Further ANOVAs revealed that the combination between perceived affordance and attractiveness is reflected in an enhanced LPP amplitude for high affording/high attractive vs. low-affording/low attractive tools [frontal: $F(3, 28) = 6.65$, $p < .002$, $\eta^2 = .38$; fronto-central: $F(3, 28) = 6.21$, $p < .003$, $\eta^2 = .36$; central: $F(3, 29) = 5.13$, $p < .008$, $\eta^2 = .32$; centro-parietal: $F(3, 29) = 4.69$, $p < .012$, $\eta^2 = .30$].

3.2.7. Late frontal positivity (LFP)

In the later time window (750–950 ms) the electrophysiological activity was still characterized by a positive deflection (see Figs. 3 and 5). This Late Frontal Positivity was enhanced on the right sites, [Side: frontal: $F(1, 12) = 7.32$, $p < .014$, $\eta^2 = .40$; fronto-central: $F(1, 16) = 6.12$, $p < .017$, $\eta^2 = .36$; centro-parietal: $F(2, 21) = 4.97$, $p < .018$, $\eta^2 = .31$; parietal: $F(2,21) = 4.17$, $p < .032$, $\eta^2 = .28$], with respect to both midline (frontal: $p < .009$, $\eta^2 = .61$; fronto-central: $p < .040$, $\eta^2 = .44$) and left electrodes (frontal: $p < .049$, $\eta^2 = .61$; fronto-central: $p < .048$, $\eta^2 = .44$; centro-parietal: $p < .048$, $\eta^2 = .43$; parietal: $p < .040$, $\eta^2 = .45$).

During this later stage, the effect of affordance disappeared and the main effect of Attractiveness emerged on fronto-central sites, [frontal: $F(1, 11) = 9.10$, $p < .012$, $\eta^2 = .45$; fronto-central: $F(1, 11) = 8.32$, $p < .015$, $\eta^2 = .4$; central: $F(1, 11) = 5.33$, $p < .041$, $\eta^2 = .33$], where

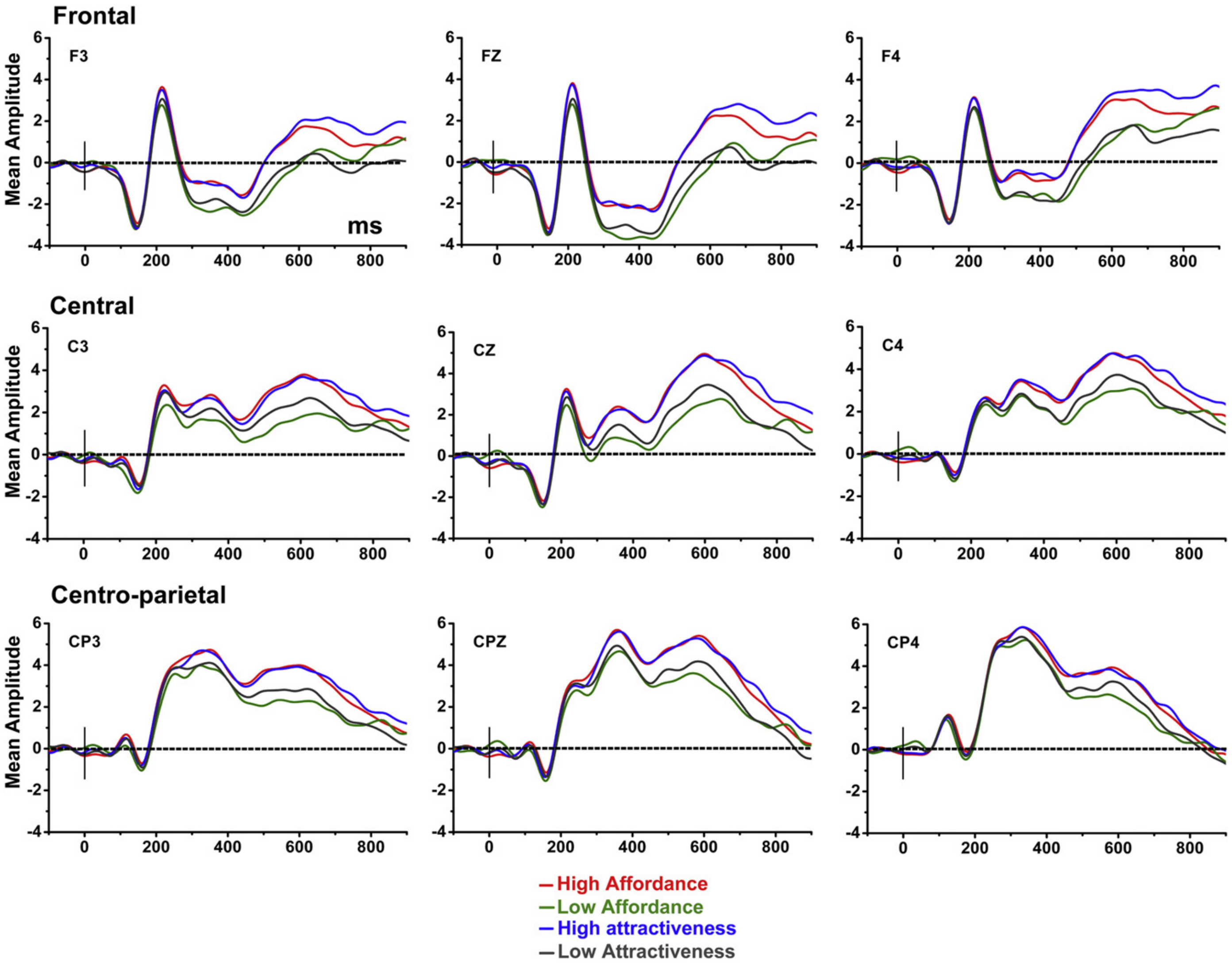

Fig. 5. Grand-averaged ERPs responses to objects judged low versus highly affordable (independent of attractiveness), and low versus highly attractive (independent of affordance). Frontal, central and centro-parietal sites are shown.

high attractive tools elicited a larger positive deflection with respect to low attractive ones. Only on frontal regions the attractiveness still interacted with affordance, [Affordance × Attractiveness: $F(1, 11) = 5.17$, $p < .044$, $\eta^2 = .32$], and the LFP's amplitude was enhanced in judging high affording/high attractive vs. high affording/low attractive tools.

3.2.8. Additional ERPs analysis

The ANOVA conducted on the P100 amplitude did not show any significant effects or interactions in both temporal and occipital sites (all $p_s > .05$). This may be related to the same average luminance across the stimuli and therefore equiluminant (Spitz et al., 1986; Tyler and Apkarian, 1985), see Figs. 4 and 6.

To have a better overall view of the effects and their distribution in the scalp topographical maps representation of the activity for selected time windows and ERPs components are provided in Fig. 7.

3.3. Summary of the ERP results

Fig. 8 shows a summary of the main effects and interactions along the considered time line that characterizes the interplay between affordance and attractiveness.

Early ERP components, i.e. both visual N100 (found on frontal and posterior clusters), were sensitive especially to the attentional effort devoted to the extraction of functional and esthetic features; in this case tools judged as low affording elicited an amplitude enhancement. Moreover, "incongruent" tools, specifically those that were evaluated as low affording but high attractive, evoked an enhanced negativity. Later on in the time course, around 180 ms the anterior P200 component was exclusively dominated by the functional and affordance-related tool characteristics with overall enhanced amplitude for highly affording tools.

The next step showed that, at the level of the N300 and P300 components, the processing of the functional attributes related to affordance was strengthened by the perceived attractiveness of objects. This mutual reinforcement was evident also from 500 to 750 ms, where high affording/high attractive yielded enhanced LPP amplitude compared to low affording/low attractive tools. Thus, between 300 ms and 750 ms we found a facilitated processing especially for tools evaluated as high affording and high attractive.

Finally, a later positivity, from 750 to 900 ms on frontal electrode clusters, was affected only by attractiveness; this effect showed a right-hemisphere lateralization whereas the electrophysiological activity before 750 ms was mainly left and midline distributed.

4. Discussion

ERPs were used to tackle the time course of the subjective evaluation of action affordance and attractiveness for visually presented everyday

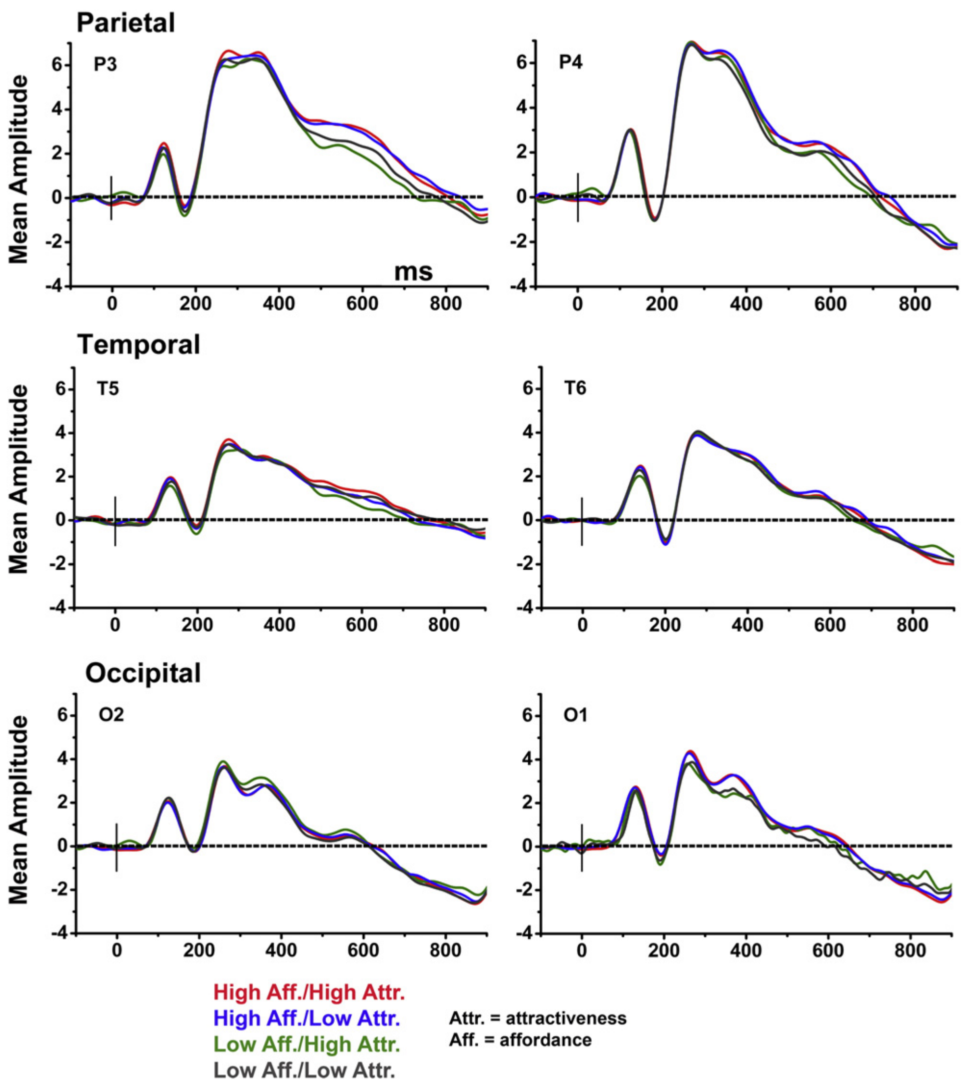

Fig. 6. Grand-averaged ERPs responses to objects judged low versus highly affordable (independent of attractiveness), and low versus highly attractive (independent of affordance). Parietal, temporal and occipital sites are shown.

tools, with the goal to explore the neural correlates of a possible interaction between these two crucial dimensions in the visual processing of tools.

The results of the present study highlight that the interplay between affordance and attractiveness plays a key role during tool evaluation throughout the entire time course of visual processing. This was shown by the evidence that tools judged as *highly affording* and *highly attractive* yielded different neural activity for several ERP components compared to the other conditions.

We found that very early in the time course (frontal N100, 90–180 ms and posterior N100, 180–260) the interaction between functional and esthetic features influenced the allocation of attentional resources. The visual N100, that may peak earlier over frontal than posterior regions of the scalp (Ciesielski and French, 1989, Mangun and Hillyard, 1991; Carretie et al., 2003), indexes an important sensory gating mechanism of attention (Foxe and Simpson, 2002; Luck and Hillyard, 1994), associated with task relevance (Ito and Urland, 2005), that only occurs when an intentional discrimination is required (Luck et al., 2000; Rugg et al., 1987; Vogel and Luck, 2000). It has been hypothesized that focusing attention on the visual stimuli increases the N100 amplitude and facilitates further perceptual processing of relevant perceptual features (Bigman and Pratt, 2004; Luck et al., 2000; Rugg et al., 1987). In this sense, the amplitude enhancement of the N100 in response to low affording/high attractive compared to high affording/high attractive tools may indicate a greater attentional effort devoted to solve the incongruence between the esthetic and motoric attributes. It might be that low affording/high attractive tools elicit a greater discordance because they simultaneously convey emotions of pleasantness but also a feeling of difficulty in understanding how they work. This possibility was also supported by our behavioral data, showing longer reaction times for judging attractiveness for low affording/high attractive tools. Interestingly, we found the same effect of discordance on both frontal and temporal sites where the enhancement for low affording/high attractive compared to high affording/high attractive tools was more evident on the left side. The modulation of the frontal and posterior N100 response to artifacts is consistent with previous studies that compared the effect of animals and artifacts in visual categorization (Antal et al., 2000, 2001; Proverbio et al., 2007). Furthermore, our posterior N100, peaking around 200 ms, resembles the negative deflection over occipito-temporal areas (N200 or N150) reflecting selective attention effects in target decision tasks using animals (Codispoti et al., 2006; Johnson and Olshausen, 2003) and objects (Van Rullen and Thorpe, 2001). The N150 has been considered to reflect perceptual selection mechanisms devoted to high level features extraction (as those selected in visual categorization) (Codispoti et al., 2006) and, more importantly, it has been demonstrated not to be dependent on low level sensory analysis (Van Rullen and Thorpe, 2001). Considering that the N150 amplitude is larger when stimuli are more difficult to

Table 2
Significant main effects and interactions obtained from the ANOVAs carried out on each ERPs component for each site considered. F and degrees of freedom are reported.

	Frontal N100	Posterior N100	P200	N300	P300	LPP	LFP
Affordance	Frontal: 7.37^{*} (1,11) Fronto-central: 9.31^{**} (1,11) Central: 10.62^{**} (1,11)	n.s	Fronto-central: 5.53^{**} (1,11) Central: 6.18^{**} (1,11)	Frontal: 5.89^{*} (1,11) Fronto-central: 5.15^{*} (1,11)	Central: 6.14^{**} (1,11) Centro-parietal: 6.34^{**} (1,11)	Frontal: 9.71^{**} (1,11) Fronto-central: 11.84^{**} (1,11) Central: 12.33^{**} (1,11) Centro-parietal: 13.26^{**} (1,11)	
Attractiveness	n.s	n.s	n.s	Frontal: 13.22^{**} (1,11) Fronto-central: 5.88^{*} (1,11)	n.s	Frontal: 8.49^{*} (1,11) Fronto-central: 6.55^{*} (1,11)	Frontal: 9.10^{*} (1,11) Fronto-central: 8.32^{*} (1,11) Central: 5.33^{**} (1,11)
Side	n.s	n.s	n.s	n.s	n.s		Frontal: 7.32^{*} (1,12) Fronto-central: 6.12^{*} (1,16) Centro-parietal: 4.97^{*} (2,21) Parietal: 4.17^{*} (2,21)
Affordance × attractiveness	Frontal: 5.87^{*} (1,11) Fronto-central: 6.59^{*} (1,11) Central: 4.45 ($p = 0.06$ – close to sign.) (1,11)	n.s	n.s	n.s	n.s		Frontal: 5.17^{*} (1,11)
Affordance × side	n.s	Occipital: 8.09^{**} (1,11) Temporal: 14.13^{***} (1,11) Parietal: 6.59^{*} (1,11)	Frontal: 5.10^{*} (1,16) Central: 7.06^{**} (2,21)	n.s	Central: 6.14^{*} (2,22)		
Attractiveness × side	n.s		n.s	n.s	Central: 4.26^{*} (2,22)		
Affordance × attractiveness × side	n.s	Temporal: 4.84^{*} (1,11)	n.s	n.s	n.s		

* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

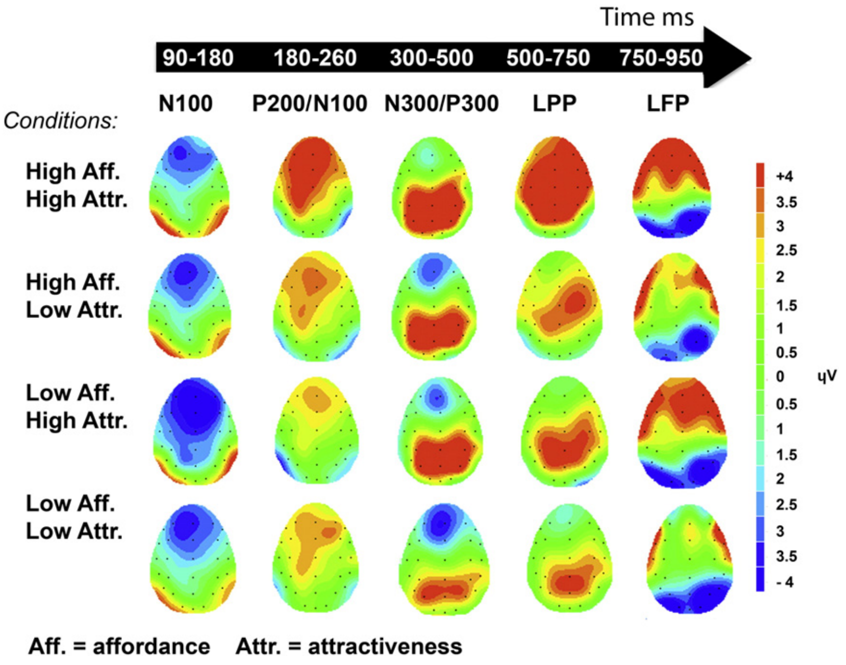

Fig. 7. Scalp topographical maps for selected ERP components in response to tools evaluate as high affording/high attractive, high affording/low attractive, low affording/high attractive and low affording/low attractive.

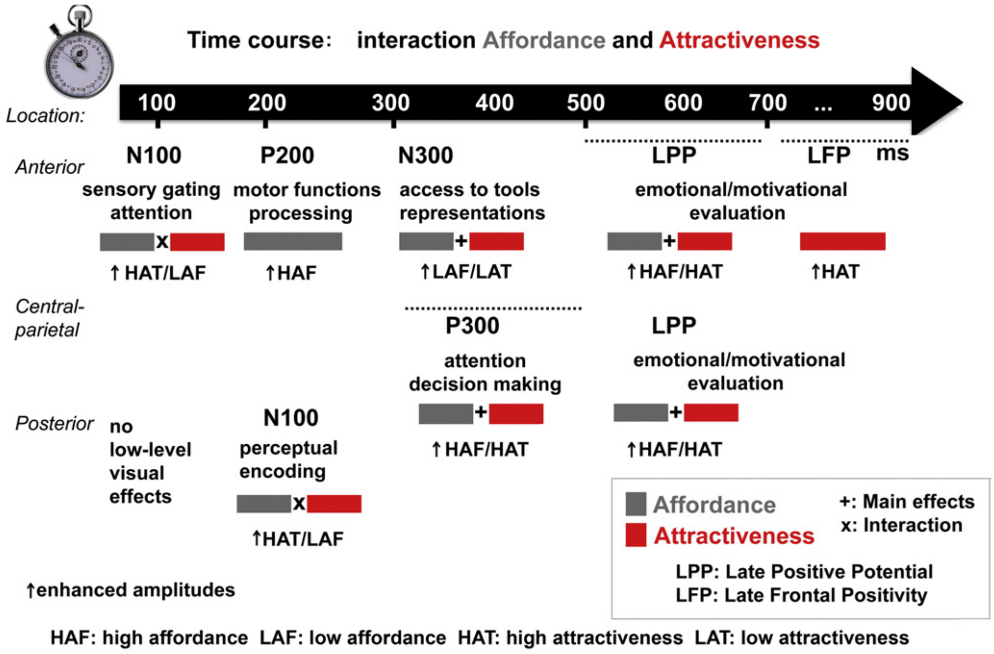

Fig. 8. Schematic summary of the main effects and interactions for affordance (in gray) and attractiveness (in red) during the different processing stages, indexed by the different ERP components, and for the different electrode locations. The amplitude enhancements for a specific condition, in a particular time window, are also reported (e.g. ⇑HAF/HAT: amplitude enhancement, compared to the other conditions, for highly affording/highly attractive tools).

process (Kiefer, 2001; Kida et al., 2011; Paz-Caballero et al., 2011; Schendan and Lucia, 2009; Tanaka et al., 1999), the reason why high affording/high attractive tools elicit a reduced N100 might be because the processing is a less-demanding processing. The present results further demonstrate how attentional mechanisms may enhance the initial stage of recognition and support the flexibility of attention in modulating different levels of information depending on the task goals (Ruz and Nobre, 2008). Taken together, these results provide evidence that early processes such as sensory gating mechanisms that are engaged in extracting salient perceptual features are facilitated for high affording compared to low affording tools. Moreover, attractiveness also influences these early stages making the coding of tools judged as high affording and high attractive easier and efficient. Interestingly, tools that subjects rated as highly attractive but low affording required more attentional resources and perceptual coding, suggesting that whenever affordance is low additional processes are needed.

Although our approach was intended to compare the neural activations related to different subjective judgments (see also Jacobs et al., 2012) one cannot exclude the possibility that that these early electrophysiological differences are related to the physical features, such as color or spatial frequency (Anllo-Vento and Hillyard, 1996; Rousselet and Pernet, 2011) that were not equated across stimuli to foster a more ecological presentation. Thus, it might be the case that some stimulus-driven features of tools evaluated as high affording/high attractive might have facilitated attentional allocation and structural analysis processes (N100). Our results did not show differences on the P100 probably because our stimuli did not differ in luminance (Cant et al., 1978) and the differences in colors were randomly distributed across categories (Luck and Hillyard, 1995). In this sense, further studies are needed to specifically explore which are the physical features that might influence the subjective evaluation and if beauty or affordance judgments are predictable from the features present in the stimuli (Jacobs et al., 2012).

Starting from 180 ms in fronto-central areas, affordance exerted a main effect in the left and midline electrodes with a larger P200 for high affording compared to low affording tools. This further supports previous electrophysiological (Proverbio et al., 2011) and neuroimaging studies (Chao and Martin, 2000; Creem-Regehr and Lee, 2005; Grafton et al., 1997; Perani et al., 1995) showing that the functional and motor properties play a key role in tool recognition. The P200 may reflect the matching between the sensory inputs and the representations stored in memory (Amsel et al., in press; Luck and Hillyard, 1994; Phillips and Takeda, 2009; Frontopolar P250 in Schendan and Lucia, 2009) and may constitute the earliest evidence that sufficient information has been accessed to influence the decision outcome in object–decision-tasks (Amsel et al., in press). Considering that the frontal P2 is typically larger for stimuli that contain task-relevant features (Luck and Hillyard, 1994; Amsel et al., in press) the neural enhancement in evaluating high affording (vs. low affording) tools suggest that affordance was the first relevant dimension in tools processing. Hence, our results confirm that the recognition of manipulable objects is prompted mainly by the motor activation intrinsically-related to a specific tool.

The main effect of action-driven affordances persisted also during the following processing stages (300–750 ms) where, interestingly, also the esthetic appraisal of the tools concurred to modulate neural activity. Between 300 and 750 ms, the electrophysiological activity was mainly left and midline sites distributed and was characterized by a fronto-central negative deflection between 300 and 500 ms (N300), a centro-parietal positivity (P300) followed by a broad distributed positive deflection between 500 and 750 ms (LPP). Our results showed both a reduced N300 and an enhanced P300 in the processing of high affording/high attractive compared to low affording/low attractive tools. This pattern of ERPs was in agreement with previous studies investigating the ERP responses in relation to object manipulability (Petit et al., 2006; Proverbio et al., 2011). The N300 may be sensitive to the recoverability of the object structure reflecting the access to both the conceptual representation system (Damasio et al., 1996; McPherson and Holcomb, 1999; Schendan and Kutas, 2007) and the motoric properties of the manipulable tools (Petit et al., 2006; Proverbio et al., 2011). Considering that the N300 may index the automatic activation of the motor schemata linked to the object's use (Petit et al., 2006; Proverbio et al., 2011) the larger negative deflection found for low affording tools may, therefore, reflect additional processing for stimuli for which it is more difficult to detect the correct motor representations. In agreement, a previous study (Proverbio et al., 2011) showed a larger anterior negativity in the passive viewing of tools vs. non-tools. Along this line of thought high affording tools facilitate the activation of motor schemata as indexed by the reduction in N300. Furthermore, previous electrophysiological research on esthetic evaluation which required explicit judgments (Jacobsen and Höfel, 2003) revealed that between 300 and 400 ms a fronto-central phasic negativity, more pronounced for non-beautiful patterns, may reflect a greater responsivity to negative than positive stimuli during the explicit evaluation processes (Ito et al., 1998; Jacobsen and Höfel, 2003; Höfel et al., 2007). Taking this previous evidence into account, our results suggest that both affordance and attractiveness work together to facilitate the tool recognition processes in the recoverability of the object representation when the tool is both high affording and high attractive.

Remarkably, the synergic effect of perceived affordance and esthetic appraisal on tool processing affected also the P300 component on central areas. The larger positive amplitude elicited by high affording/high attractive, compared to low affording/low attractive tools, might suggest differences in the attentional updating process (Soltani and Knight, 2000; Polich, 2007). Taking into account that the P300 has been shown to be sensitive to stimuli arousal value (Delplanque et al., 2006), it may be that the greater posterior attentional system activity for high affording/high attractive tools reflects the focusing of attention on arousing positive valence stimuli, in agreement with previous studies (Delplanque et al., 2004, 2006; de Tommaso et al., 2008; Dolcos and Cabeza, 2002). This possibility was also strengthened by the evidence of a larger centro-parietal P300 for tools compared to non-tool objects in a passive viewing paradigm (Proverbio et al., 2011). This P300 enhancement has been interpreted as a sign of increased attention allocation toward tools due to their attention-capturing capabilities as salient and arousing objects (Proverbio et al., 2011).

The same arousal-related effect could also influence further stages of processing, from 500 to 750 ms, where the LPP was enhanced for tools perceived as high attractive and affording. In this regard the LPP has been mainly related to emotional processing (Cuthbert et al., 2000; Ferrari et al., 2011; Righi et al., 2012) reflecting the level of arousal triggered by the stimulus (Anokhin et al., 2006; Schupp et al., 2004; Hajcak et al., 2006).

Overall, our results indicated that between 300 and 750 ms the processing of both affordance and attractiveness exerted an additive reinforcement in the processing of tools simultaneously evaluated as high attractive and high affording. Differently, when tools were judged as low affording and low attractive the access to the stored action and conceptual knowledge may be more effortful, as suggested by the larger N300 amplitude. Furthermore, less attention and affective processing may be devoted to low affording/low attractive tools because of their poor appeal, as indicated by the reduction on both P300 and LPP amplitudes. Remarkably, all the neural activity lasting until 750 ms was mainly left-sided distributed in agreement with previous research reporting that the manipulable object processing had a prevalence in left-sided generators (Cardellicchio et al., 2011; Chao et al., 1999; Chao and Martin, 2000; Martin et al., 1996; Perani et al., 1995; Pulvermüller et al., 1999; Vingerhoets, 2008; Vingerhoets et al., 2013). As to the predominance of the neural activity in the left regions, our subjects were all right-handed and hence the motor schemata activated by the observed tools evoked stronger right hand involvement, which is represented in the contralateral motor cortex (left).

Later on in the time course, the main effect of affordance disappeared and attractiveness dominated and modulated the electrophysiological activity, from 750 to 900 ms, which was characterized by a right distributed positive frontal deflection (LFP) that was larger for high attractive compared to low attractive tools. This positivity might be a later frontal reflection of the LPP. The LPP, especially with a stronger right-hemispheric distribution, has been associated to both evaluative (Cacioppo et al., 1996; Crites and Cacioppo, 1996) and esthetic categorization tasks (Höfel et al., 2007; Jacobsen and Höfel, 2003). In line with previous studies, our finding of an attractiveness-related right-distributed positive enhancement may suggest that the specific evaluation of esthetic (appraisal) emerges later on during the tools processing. More remarkably, in the frontal areas the interplay between attractiveness and affordance still influenced tools processing and the LPP was enhanced for objects evaluated as high affording and high attractive with respect to tools evaluated as high affording but low attractive.

All in all, the present study shows that affordance and attractiveness can be additive or might interfere by creating conflicts that are responsible for an increase in processing time (this was evident for the reaction times). Early on, more effort in the attentional and perceptual processes is devoted to solve the incongruence between attractiveness and motor-related features, while later in the time course processing might be facilitated for those tools simultaneously evaluated as high affording and high attractive. Later on, from 300 to 750 ms, affordance and attractiveness are jointly related in their neural responses and are strengthened by each other. In line with the design perspective suggesting that esthetically pleasing objects are considered to be more effective (Chawda et al., 2005; Norman, 2003; Tractinsky, 1997; Tractinsky et al., 2000; Xenakis and Arnellos, 2013) our findings stress the important additive interplay of attractiveness and affordance in the cognitive processing of tools. However, the present results highlight a key role played by affordance in the early stage of processing (P200) suggesting that the detection of the motoric and functional attributes of tools is the first step of tools evaluation, since it occurs before esthetic evaluation which exerts an additive effect only from 300 ms. This crucial role of affordance is not surprising considering that tools are strictly action-related and that they have to be processed rapidly for an efficient adaptive behavior. Moreover, this evidence is in agreement with the designer's vision of a main role of affordance in the artifacts' evaluation (Maier et al., 2009).

4.1. Conclusions

In conclusion, this is the first study that investigated the effects of the interaction between action affordance and tool attractiveness on the neural activity during an explicit evaluation task. On one hand we highlight a key role played by affordance during the early processing stages, with the detection, extraction and matching of motoric and functional attributes. On the other hand, our data clearly shows that brain activity is facilitated and specifically tuned by tools perceived as high affording but also high attractive, confirming that also likeability and emotional responses play a relevant role. The suggestion from this study for designers might be that although highly attractive objects are very powerful in evoking neural responses, they must be combined with high affording properties. Otherwise, cognitive processing is slowed down and additional attentional and perceptual processes are required. Furthermore, the present results may be also of some interest for neuropsychology and rehabilitation because, given the strong neural interaction we found between affordance and attractiveness, it may be that the use of high affording/high attractive tools might facilitate the process of recovery of apraxia.

A final consideration is that the present study might be considered a starting point for several further explorations involving interdisciplinary perspectives. A first topic to address could be to expand the present results to object processing when an explicit evaluation is not required. A further issue could be to explore which stimuli features foster evaluative judgments.

All in all, this study sheds light on the importance of the relationship between affordance and attractiveness by showing that things that are perceived to work better and to be highly attractive have a privileged and selective neural activation.

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