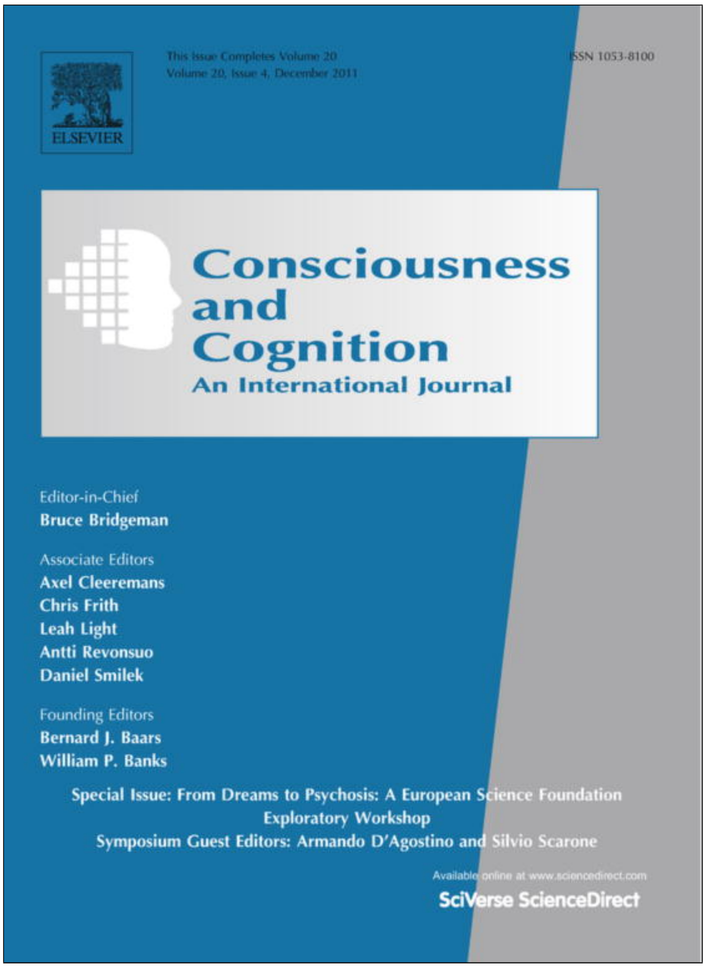
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Perceptual awareness and categorical representation of faces: Evidence from masked priming

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ABSTRACT

How internal categories influence how we perceive the world is a fundamental question in cognitive sciences. Yet, the relation between perceptual awareness and perceptual categorization has remained largely uncovered so far. Here, we addressed this question by focusing on face perception during subliminal and conscious perception. We used morphed continua between two face identities and we assessed, through a masked priming paradigm, the perceptual processing of these morphed faces under subliminal and supraliminal conditions. We found that priming from subliminal faces followed linearly the information present in the primes, while priming from visible faces revealed a non-linear profile, indicating a categorical processing of face identities. Our results thus point to a special relation between perceptual awareness and categorical processing of faces, and support the dissociation between two modes of information processing: a subliminal mode involving analog treatment of stimuli information, and a supraliminal mode relying on discrete representation.

1. Introduction

How do internal categories influence the way we experience the external world? Categorical perception happens when an external stimulus, situated in a continuous physical space, is associated during its perceptual processing with one internal psychological category. In various studies on speech perception, color vision, and face perception, this phenomenon has been mirrored by behavioral or neural responses that have a non-linear relation to the stimulus variations (see Harnad (2005), for a general review): while the stimulus varies smoothly along a continuous dimension, performance in identification or in discrimination tasks exhibit sharp transitions at boundaries between categories.

Categorical perception has been studied along three domains. It was first shown for speech sounds (i.e. phonemes) in human subjects (e.g. Dehaene-Lambertz, 1997; Liberman, Harris, Hoffman, & Griffith, 1957) as well as in various non-human species such as chinchillas (Kuhl & Miller, 1975) and crickets (Wyttenbach, May, & Hoy, 1996). Categorical perception effects have been also studied in color vision, in relation to the Whorfian hypothesis (Whorf, 1956), and the possibility that color words in our native language shape the way we perceive colors in the world (see for instance Drivonikou et al., 2007; Gilbert, Regier, Kay, & Ivry, 2006; Siok et al., 2009; Tan et al., 2008; Thierry, Athanasopoulos, Wiggett, Dering, & Kuipers, 2009; Winawer et al., 2007). Finally, a third and more recent line of research on categorical perception has focused on face stimuli, with the recent development of the morphing technique offering the opportunity to create physical continua between two face pictures that elicit abrupt transitions in perception (see Fig. 1). With this technique, categorical effects have been shown

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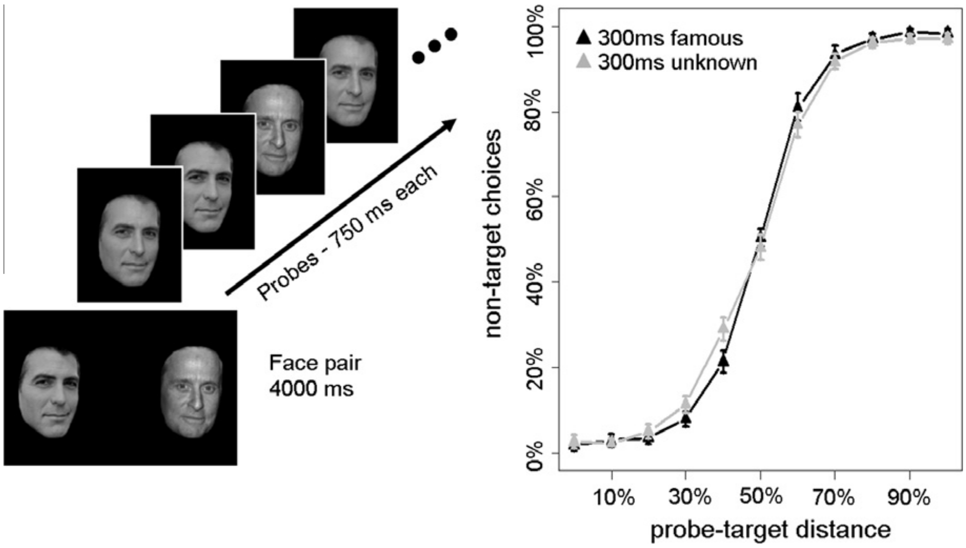

Fig. 1. (left) Schematic representation of a pre-test experiment (identification of the morphed faces). For each pair, participants ($N = 8$) were presented first with both faces of the pair for 4000 ms, and then with 3 randomized sequences of the 11 morphs created from that pair. For each morph they had to indicate on the keyboard the initial face it was closer to (left or right). Each morph was presented centrally for 750 ms after a fixation cross (500 ms), and was followed by a black screen until the response. (right) Participants' responses: percentage of trials in which the probe was classified as the target as a function of probe–target similarity, error bars represent SEM.

for face stimuli varying along specific features, such as emotional facial expressions (Calder, Young, Perrett, Etcoff, & Rowland, 1996; Campanella, Gaspard, et al., 2002; Campanella, Quinet, Bruyer, Crommelinck, & Guerit, 2002; Etcoff & Magee, 1992), face identity (Beale & Keil, 1995; Campanella, Hanoteau, Seron, & Bruyer, 2003; Campanella et al., 2000; Rothstein, Henson, Treves, Driver, & Dolan, 2005), race (Levin & Beale, 2000) and gender information (Campanella, Chrysochoos, & Bruyer, 2001).

Categorical perception has, thus, been a key issue in psychology for decades, for it is said to constitute the "groundwork of cognition" (Harnad, 1987, 2005). Yet, the relation between categorical perception and perceptual awareness of a stimulus has been uncovered so far. Here, we address this issue by focusing on the categorical perception of faces, and by studying whether it can occur in the absence of awareness (i.e., for a stimulus processed under subliminal conditions), or whether it actually remains restricted to conscious perception (i.e., restricted to supraliminal conditions). This question also echoes with the recent proposition that subliminal and conscious perception might differ in terms of processing mode (Sackur & Dehaene, 2009), which we will introduce now.

While unconscious cognition was considered controversial until recent years, a growing corpus of evidence now demonstrates that subliminal stimuli (i.e. stimuli that can not be reported or discriminated by the observer) can nevertheless produce a significant impact on brain and behavior (for a recent review see Kouider & Dehaene, 2007). As an example, cognitive control functions implemented in the frontal cortex were commonly assumed to be a restricted stronghold inaccessible to subliminal stimuli, but recent studies challenged this view by showing that strictly subliminal stimuli can reach frontal regions involved in inhibition mechanisms (van Gaal, Ridderinkhof, Fahrenfort, Scholte, & Lamme, 2008), or task control (Lau & Passingham, 2007). Subliminal stimuli might thus reach the highest levels of processing in the cognitive system. Yet, one possibility is that unconscious cognition might not be limited in terms of processing depth, but actually in terms of processing *mode*. For instance, it has been proposed recently that a stimulus reaching perceptual awareness could be processed in a discrete fashion, whereas a subliminal stimulus receives only analog processing (Sackur & Dehaene, 2009). Following this perspective, a computational switch would occur between analog subliminal processing reflecting linearly the continuous nature of physical stimuli and discrete information processing under situations of perceptual awareness. In other words, the flow of information following a subliminal stimulation might reach high-level processing regions, but it might still be of a different kind compared to the conscious stimulation: in the subliminal case it would be linearly related to the features of the external stimulation, while in the conscious case the information in the stimulus would be rendered discrete. The fact that conscious stimuli benefit from more efficient processing, being less corrupted by noise accumulation across chained operations (Sackur & Dehaene, 2009) or along time (Dupoux, de Gardelle, & Kouider, 2008), provides initial support for this hypothesis.

In this study, we considered this hypothesis at the level of perceptual processing, and we reasoned that the best candidates for supporting the discretization process that would coincide with conscious perception are the categories that support categorical perception of the stimulus (e.g. the identity of a face stimulus). Thus, we proposed that categorical perception might occur specifically for perceptual stimuli processed under supraliminal conditions, and would be absent when the stimuli are subliminal. An alternative line of reasoning, however, would be to consider that because categorization is a fundamental aspect of cognition (e.g. for Harnad, 1987, 2005, ‘‘cognition is categorisation’’), it will occur irrespectively of the subliminal vs. supraliminal conditions of perception.

In order to test empirically this issue, one would need to (1) construct stimuli varying continuously in physical features, (2) have a measure of the processing of these stimuli under subliminal and supraliminal conditions of perception, (3) verify that in the supraliminal case this measure shows a non-linear relation with the physical features in the stimulus (as shown in previous research), and finally (4) test whether in the subliminal condition this measure is linearly or non-linearly related with the physical features.

Here, we applied this approach to face stimuli, capitalizing on the use of face morphing as a tool for generating face stimuli varying continuously between two original pictures. Past research on face perception has demonstrated the power of this technique, for instance by showing that the discrete identity-based information in a face stimulus can be dissociated from its physical information, which is of a continuous nature (e.g. Beale & Keil, 1995; Campanella, Hanoteau, Seron, & Bruyer, 2003; Campanella et al., 2000; Rothstein et al., 2005). To address our question, we created morphed faces and measured how they are processed via priming, as in Rothstein et al. (2005). However, in contrast with these previous studies using only supraliminal conditions, we assessed the perception of these morphed stimuli by using a masked face priming method recently developed in our lab (de Gardelle & Kouider, 2010; Kouider, Eger, Dolan, & Henson, 2009), which allowed us to test the perception of these morphed faces both under subliminal vs. supraliminal conditions. Perceptual awareness was manipulated by varying the duration of the primes (here 43 ms vs. 300 ms, respectively) and controlled in a subsequent visibility test.

Participants were asked to make a simple binary decision on face targets (Famous/Unknown task in Experiment 1; French/American nationality task in Experiment 2), which were preceded by visible or invisible morphed primes that were irrelevant to the task. These primes were morphed faces extracted from continua created by morphing the target face with another face associated with the same response category in the current task, to test perception while avoiding any confound with decision or motor components. Pre-testing of these stimuli revealed that they elicited clear transitions in identification (Fig. 1), as in previous studies (e.g. Rothstein et al., 2005). Assuming that response times would reflect the perceptual similarity between the morphed prime and the target, a basic test for categorical effects in the perception of the prime is the presence of a non-linear profile in these responses times as a function of the distance between the prime and the target on the morphing continuum.

2. Materials and methods

2.1. Participants

All participants in this study were students recruited from Paris universities, reporting normal or corrected vision, and paid for their participation. Sixty-two subjects participated in Experiment 1 (priming and visibility tests), 20 in a post-test (fame judgments on morphed faces), and 34 in the Experiment 2 (priming test).

2.2. Stimuli

Images used were gray-scale photographs of faces, cropped to show face only on a black background, and matched for face size. In Experiment 1 we used 88 faces (half famous, half unknown). In Experiment 2 we used 80 famous faces (half French, half American). Morphing continua were created by grouping them into pairs with same gender and response category (fame in Experiment 1, nationality in Experiment 2), while ensuring a possible morphing between the two faces of the pair. Then, for each pair, we used the FantaMorph software to create images morphed with different degrees (0% to 100% in steps of 10%). Finally, all images were corrected in luminance to have the same global energy. Masks images were meaningless patterns artistically created using Adobe Photoshop by blending 6 randomly chosen images from a different stimulus set (2 non-famous faces, 2 watches, 2 flowers). The average luminance, contrast, and shape of the masks were set to be similar to those of the faces. Primes were beforehand reduced to 80% of the size of the target, ensuring correct masking conditions and eliminating repetition effects at the pixel level. All tests were run using the Cogent Toolbox with Matlab, on a 17″ CRT screen refreshed at 70 Hz, and viewed from a 60 cm distance.

2.3. Priming test

All trials were as follows (see Fig. 2): a fixation cross appeared on the screen for 300 ms, then a forward mask (300 ms), followed by the prime (43 or 300 ms), a backward mask (29 ms) and the target face (700 ms). Participants were instructed to decide as quickly as possible whether the target face belonged to a famous person or not (Experiment 1), or to a French or American personality (Experiment 2), while ignoring other visual events. Prime duration was manipulated between participants and in the 43 ms (subliminal) groups participants were not informed of the presence of the primes. All participants started with a training block, followed by experimental blocks (11 blocks of 88 trials in Experiment 1, 12 blocks of 80 trials in Experiment 2), each block containing all the targets. On each trial, the prime was extracted from the continuum created with the target. For each subject, each target was presented with all the different possible primes (taken from its continuum with a variable prime–target morphing distance) over the course of the experiment.

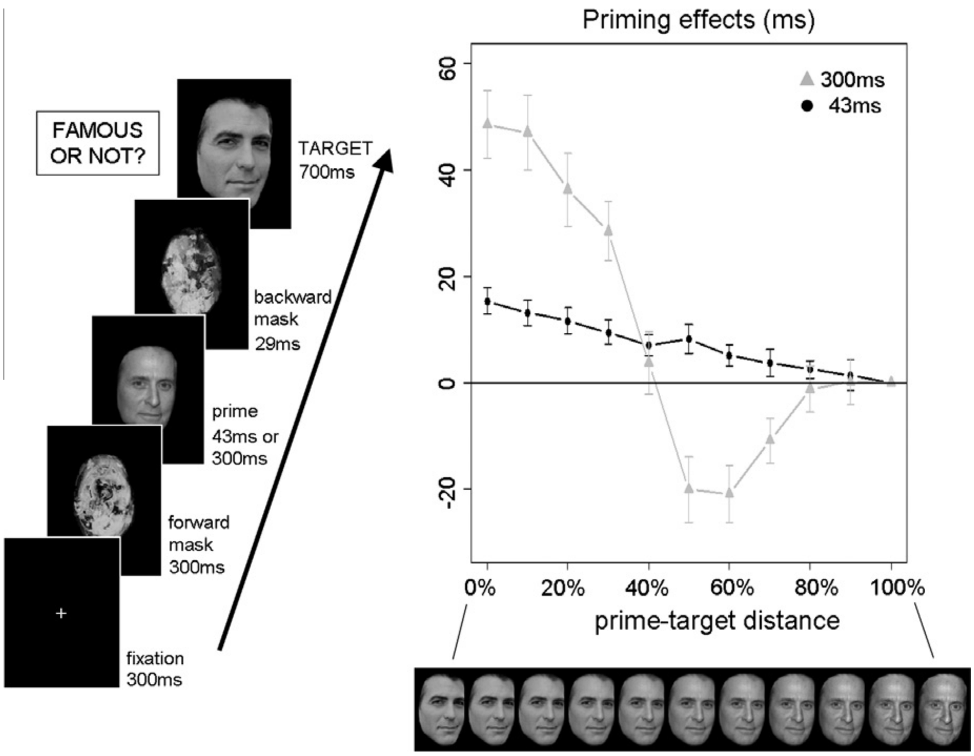

Fig. 2. (left) Trial structure for the priming paradigm. Participants had to respond as fast and accurately as possible to the target face (fame judgment task in Experiment 1, nationality judgment in Experiment 2), which was preceded by a 43 ms prime or by a 300 ms prime extracted from a morphing continuum. (right) Priming effects for famous face trials in Experiment 1 as a function of prime duration, for each prime–target distance (*x*-axis, 11 levels tested). Error bars represent SEM. Below this graph is presented all the faces for one continuum between two famous faces.

2.4. Statistical analysis

We excluded from our analyses subjects whose accuracy was below 70% in one of the response categories (9/62 subjects in Experiment 1, 5/20 in the post-test, 8/34 in Experiment 2), and one subject of Experiment 1 with extremely slow response times (that is, RT > 900 ms = mean + 3SD). These participants were also excluded from the analysis of the visibility test. After that, in Experiment 1 there were 31 participants in the subliminal group and 21 participants in the supraliminal group, and in Experiment 2 there were 13 participants in each group. We excluded then error trials (6%) and RT slower than 700 ms (i.e. when the response arrived after the offset of the target, an additional 11%). For each participant, priming effects were computed (across all pairs) in the two target category conditions as a function of the prime–target distance on the morphing continuum (11 levels in Experiment 1, 6 in Experiment 2) by taking as a baseline the trials in which the target was preceded by the other face of the pair it belonged to (i.e., the rightmost point in Figs. 2 and 4 is at zero by definition, the leftmost point is the 'classic' repetition priming effect, and positive priming effects correspond to speed up of responses). Priming effects were then submitted to an ANOVA with these within-subject factors plus prime duration as a between-subject factor.

Finally, the linearity or non-linearity of the priming profile was assessed using a model comparison approach. For each subject, we computed the Akaike Information Criterion (AIC; Akaike, 1973; see also Myung, 2000) for three models, in which priming was predicted by the prime–target distance with a linear (AIC_L), polynomial (AIC_P), or spline (AIC_L) function. The AIC computation incorporates the goodness of fit between the model and the data with a penalty corresponding to the number of free parameters of the model. This method allows for comparing models with different numbers of parameters, with lower AIC values for "better models". The AIC values were then included in an ANOVA with model types (within-participant) and visibility (between-participant) as factors, and subjects to paired *T*-tests comparisons.

3. Results

3.1. Experiment 1: Morphed face priming in a fame judgment task

Mean accuracy in the fame judgment task was 93.5% (SD = 4.5%) and mean RT was 548 ms (SD = 102 ms). The ANOVA on priming effects revealed main effects of distance ($F(10, 500) = 54.6$, $p < .001$), visibility ($F(1, 50) = 22.62$, $p < .001$), interactions between distance and visibility ($F(10, 500) = 39.98$, $p < .001$), visibility and familiarity ($F(1, 50) = 8.95$, $p < .01$), distance and familiarity ($F(10, 500) = 12.19$, $p < .001$), and a triple interaction between distance, familiarity, and visibility ($F(10, 500) = 11.11$, $p < .001$). Planned *T*-tests (see Table S1) revealed that unlike famous targets, unknown targets did not show any subliminal priming, consistently with previous studies (Kouider et al., 2009). Thus, subsequent analyses focused on priming effects for famous face trials only to assess how these effects might differentially depend on the prime–target distance under subliminal and supraliminal conditions (analyses of priming for unknown faces are presented as Supplementary material).

The distance × visibility ANOVA restricted to famous face trials revealed a main effect of distance ($F(10, 500) = 44.65$, $p < .001$), no main effect of visibility ($p > .1$) and an interaction between distance and visibility ($F(10, 500) = 31.85$, $p < .001$). Priming was affected by the prime–target distance in both the subliminal ($F(10, 300) = 8.67$, $p < .001$), and supraliminal ($F(10, 200) = 40.44$, $p < .001$) conditions, confirming that priming was obtained in both conditions. However, as can be seen in Fig. 2, the two conditions show different profiles: subliminal priming appears to reflect linearly the prime–target distance on the continuum, while supraliminal priming is clearly non-linear.

This difference between the subliminal and supraliminal profiles was confirmed by the ANOVA on AIC values, which showed a significant interaction between visibility and model type ($F(2, 100) = 45.54$, $p < .001$), along with main effects of visibility ($F(1, 50) = 72.70$, $p < .001$), and type ($F(2, 100) = 8.11$, $p < .001$). Restricted analyses revealed that in the subliminal condition the three tested models performed differently ($F(2, 60) = 5.24$, $p < .01$), with lower AIC values indicating better performance for the linear model (means: $AIC_L = 82.18$, $AIC_P = 83.32$, $AIC_S = 83.34$; paired *T*-tests comparisons: $T_{Lvs.S}(30) = 2.29$; $T_{Lvs.P}(30) = 2.37$, both $p < .05$; $T_{Svs.P} < 1$), while crucially, for supraliminal priming it was the opposite, with better performances for non-linear models (effect of model type: $F(2, 40) = 40.41$, $p < .001$; means: $AIC_L = 101.95$, $AIC_P = 97.75$, $AIC_S = 96.81$; paired comparisons: $T_{Lvs.S}(20) = 6.60$, $T_{Lvs.P}(20) = 6.16$, $T_{Svs.P}(20) = 4.52$, all $p < .001$). Thus, this analysis provides a quantitative confirmation that subliminal priming was more consistent with a linear profile while supraliminal priming was more consistent with a non-linear profile. In other words, while subliminal faces received enough processing to induce priming effects, these effects reflected the prime–target relation in an analog way, and only became linked to the identity of the face for supraliminal primes.

3.2. The morphed intruder effect

Unexpectedly, supraliminal priming became negative in the middle of the continuum between two famous faces (Fig. 2, right), and this dip was reliable across participants (see Table S1). We conjectured that this could be due to the intermediate morph on the continuum between two famous faces being perceived as an unknown face, and conflicting with the subsequent famous target at the decision/motor stage of the fame judgment task. We conducted a post-test experiment to assess this interpretation, in which 20 new subjects made the fame judgment directly on the morphed items presented for 300 ms (we just replaced the target face by a mask in the supraliminal condition of Experiment 1). Overall the degree of morphing between the two famous faces affected participants' fame judgment ($F(10, 140) = 18.20$, $p < .001$), and intermediate morphs between two famous faces were classified as unknown more than 25% of the time (see Fig. 3). Thus, participants perceived this intermediate face in the continuum as a "morphed intruder", that is a third and non-famous person, distinct from the two famous faces it was made of.

This counter-intuitive finding can be accounted for by computational models of face categorical perception that represent the known faces as attractors of the network, this mechanism subtending categorical responses of the network. In particular, previous work along these lines suggested that the attractor basin narrows with more familiar faces (Tanaka, Giles, Kremen,

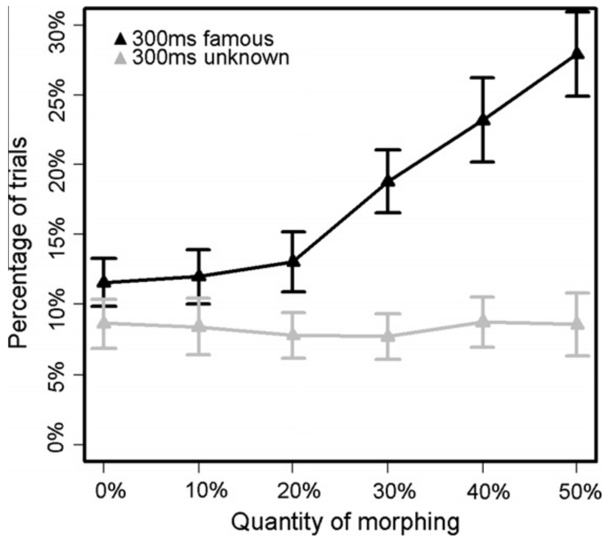

Fig. 3. Post-test (fame judgment on morphed faces), showing the "morphed intruder effect". (*x*-axis) Morphing distance between the morphed face and the closest end-point of the continuum. (*y*-axis) Percentage of morphs between two famous faces classified as non-famous (in black), and morphs between two non-famous faces classified as famous (in gray). Error bars represent SEM.

& Simon, 1998). In our paradigm each continuum was extracted from two highly familiar (i.e., famous) faces, which would have very narrow attractor basins leaving an intermediate zone without an attractor between them. Then, in the supraliminal presentation condition the activity elicited by an intermediate stimulus would not converge to one of the attractors. Consequently the stimulus would be interpreted as a face of an unknown person.

The results described so far thus dissociate between supraliminal and subliminal conditions of perception. In the supraliminal case, the "morphed intruder" effect shows that participants consciously perceiving a morphing continuum between two known faces actually see another identity in between the two known faces. When these morphed faces are used as primes, then they facilitate the perceptual processing of the target in a non-linear manner that reflects this identity-based processing of the prime (with not two but maybe three identities in the continuum). By contrast, in the subliminal case the same morphed faces elicit priming that reflects the physical information in an analog manner.

We acknowledge that the non-linearity observed in the supraliminal condition reflected, at least in part, the motor conflict due to the morphed intruder effect. To account for that, we ran an additional analysis on the slope of the priming effect as a function of morphing, in which we included only the extreme values of the continuum that do not seem to be affected by the "morphed intruder effect". For each participant we computed slopes (priming difference divided by the morphing difference) between three pairs of data points (0–20%, 20–80%, and 80–100%). Separate ANOVAs showed that the three slopes differed between the three pairs for the supraliminal data ($F(2, 40) = 3.75$, $p < .05$), but not for the subliminal data ($F < 1$). The difference between the two profiles was confirmed by a significant visibility × pair interaction ($F(2, 100) = 3.62$, $p < .05$), showing that the change in slope for priming effects occurred only under supraliminal conditions. Finally, to replicate the dissociation while eliminating this motor aspect, we conducted a second experiment, using again famous faces but a task that was unrelated to familiarity. A new group of participants had to judge the nationality (French vs. American) of famous target faces that were preceded by subliminal or supraliminal morphed primes. This task would not eliminate the intermediate face being consciously perceived as an unknown person. However as this morphed intruder prime will not be associated with any clear response category in the nationality task (unknown faces can be classified indifferently as French or American) we expect here to reduce the motor conflict effect observed in the first experiment.

3.3. Experiment 2: Morphed face priming in a nationality judgment task

Mean accuracy in the nationality judgment task was 90.0% (SD = 6.8%) and mean RT was 564 ms (SD = 111 ms). We applied the same analyses approach as in Experiment 1. The global ANOVA on priming effects revealed main effects of visibility ($F(1, 24) = 10.03$, $p < .01$, with 4 ms subliminal priming vs. 17 ms for supraliminal priming), and distance ($F(5, 120) = 47.24$, $p < .001$), and an interaction between distance and visibility ($F(5, 120) = 29.97$, $p < .001$). No effects or interactions with nationality reached significance, so subsequent analyses did not include this factor. Planned *T*-tests across subjects assessed priming reliability in each condition (see Table S2), and revealed significant priming effects in both the subliminal and supraliminal conditions.

Two separate ANOVAs confirmed the effect of distance on both subliminal ($F(5, 60) = 7.03$, $p < .001$) and supraliminal priming ($F(5, 60) = 41.53$, $p < .001$). As can be seen in Fig. 4, the patterns here also differed between these two situations, with subliminal priming appearing linear while supraliminal priming showing a non-linear profile.

As above, we ran a model comparison analysis to quantify this dissociation. The difference between these profiles was confirmed by the ANOVA on AIC values, which revealed crucially an interaction between group and type ($F(2, 48) = 22.08$, $p < .001$), along with a main effect of group ($F(1, 24) = 18.82$, $p < .001$), and no main effect of type ($F(2, 48) = 1.15$, $p > .1$). Here again, subliminal priming was better fitted by the linear model (effect of model type: $F(2, 24) = 14.36$, $p < .001$; means: $AIC_L = 87.30$, $AIC_P = 89.35$, $AIC_S = 89.44$; paired comparisons: $T_{Lvs.S}(12) = 4.05$, $T_{Lvs.P}(12) = 3.58$, both $p < .01$, $T_{Svs.P}(12) = 1.10$, $p > .1$), while supraliminal priming was better fitted by non-linear models (effect of model type: $F(2, 24) = 10.78$, $p < .001$; means: $AIC_L = 103.54$, $AIC_P = 100.50$, $AIC_S = 100.03$; paired comparisons: $T_{Lvs.S}(12) = 3.44$; $T_{Lvs.P}(12) = 3.18$, both $p < .01$; $T_{Svs.P}(12) = 1.83$; $p < .10$). The pattern of result in Experiment 2 thus fully replicates the dissociation between subliminal and supraliminal priming observed in Experiment 1.

3.4. Visibility test for the primes

Finally, the subliminal and supraliminal character of priming was confirmed by the visibility test for participants of Experiment 1 (note that the visibility conditions were identical in Experiments 1 and 2). Following the priming test, participants were debriefed about the presence of the primes. Then they were presented with the same stimulation, and performed a two-alternative forced choice deciding which image corresponded to the prime between the actual prime and a distracter, both presented clearly at the end of each trial. Participants' performances differed between the two visibility conditions ($F(1, 50) = 165.85$, $p < .001$), with high performances indicating supraliminal processing in the 300 ms condition (mean accuracy = 80.3%, comparison against the chance level of 50%: $T(20) = 11.1$, $p < .001$), but chance level performances in the 43 ms condition (mean accuracy: 50%), confirming the subliminal nature of prime processing in this condition (see Supplementary material for more detailed analyses).

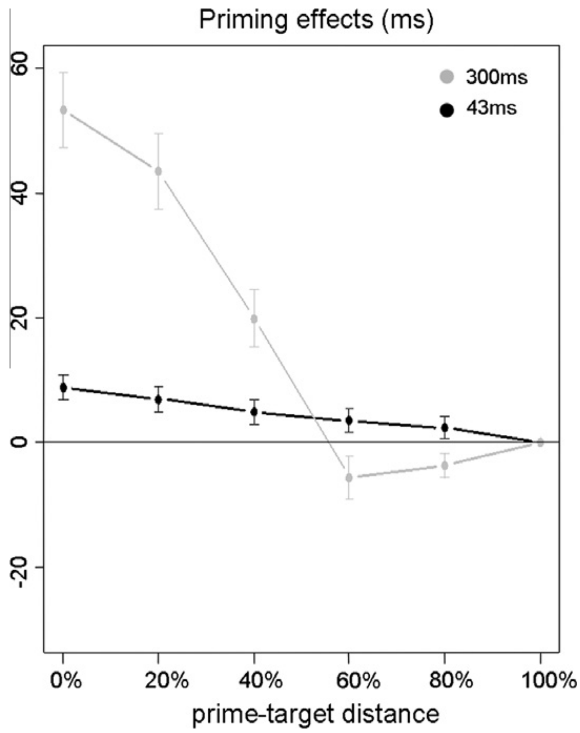

Fig. 4. Priming effects in Experiment 2, as a function of prime duration, for each prime–target distance on the morphing continuum (*x*-axis, six levels tested). Error bars represent SEM.

4. General discussion

In this study, we investigated the relation between perceptual awareness and categorical perception. To do so, we created morphed face stimuli and them as subliminal and supraliminal primes in a masked priming paradigm. In two experiments using different tasks and participants, we observed a clear dissociation between priming for visible and invisible primes: subliminal priming reflected linearly the prime–target distances on the morphing continuum, while supraliminal priming revealed a non-linear profile indicating categorical perception of the identity of the prime faces (Figs. 2 and 4).

Our study thus indicates that categorical perception does not occur for subliminally perceived faces. At this point, we want to clarify that this result does not conflict with past studies of subliminal perception that have used categorization tasks. Indeed, using masked priming, it has been shown for long (in fact, since Forster & et Davis, 1984; Marcel, 1983) that subliminally perceived stimuli can elicit priming effects during conscious categorization judgments on a subsequent target. Besides, using direct tasks, it has been shown that participants can classify very rapidly a complex visual stimulus as containing a predefined high-level category (e.g. animal vs. cars) on the basis of the unconscious feedforward processing sweep (e.g. Thorpe & et Fabre-Thorpe, 2001). Thus subliminal stimuli can be processed during categorization tasks, and moreover this processing depends on the particular current task (Nakamura, Dehaene, Jobert, Le Bihan, & et Kouider, 2007; Nakamura et al., 2006), and on participant's expectations about the stimulus' identity (e.g. Kunde, Kiesel, & Hoffmann, 2003) or apparatus (e.g. Naccache, Blandin, & Dehaene, 2002). However, the focus of all these studies was not on the particular issue of unconscious categorical perception *per se*: they did not investigate the linear or non-linear responses to morphed stimuli or physical continua presented under subliminal conditions. In the present study, we show that even if subliminal faces can be processed during categorization tasks, they do not necessarily receive categorical processing but elicit priming effects linearly related to their physical information. In particular they contrast with supraliminal faces, whose identities are perceived in a categorical manner (e.g. Rothstein et al., 2005), and for which priming effects relate non-linearly to their physical information and incorporate a categorical, identity-related, information.

Thus, our results support the recent proposal that the stimulus information being processed in a discrete way is tightly correlated with conscious access, while unconscious processes rely on analog computations (Sackur & Dehaene, 2009). Interestingly, one major functional advantage of discrete/categorized processing is to allow for stabilizing the information carried by the stimulus, and limiting the accumulation of noise. Indeed, once one signal is associated with one category or discrete symbol, its representation is more distant to the other categories (i.e. separated by a categorical boundary) and corrupting this signal with noise would much less easily set it to a different category. Notably, this advantage fits well with specific features of conscious processing which have been observed empirically, such as information maintenance in time (Dupoux, de Gardelle, & Kouider, 2008), and in the chaining of multiple operations (Sackur & Dehaene, 2009). Yet, the influence from discrete categories renders conscious processing slightly unfaithful to the stimulus, and by contrast unconscious perception is much noisier but also more faithful to the continuous nature of physical stimuli given that it is free from these influences. While counterintuitive, this description of our data is surprisingly consistent with a recent experiment of ours (de Gardelle & Kouider, 2010) using low-level visual stimuli. Indeed, we have found that perception of orientation in Gabor patches was also noisier but more faithful in subliminal compared to supraliminal conditions, under which participants responses were more precise but also more influenced by discrete visual categories (tilted vs. cardinal orientations).

Importantly, the observed correlation between categorical priming effects and awareness leaves open the question of their causal links (i.e., whether categorical processing precedes and induces consciousness or vice versa). Several influential cognitive theories of consciousness have proposed that a stimulus is consciously accessed as a function of its ability to win the competition for global broadcasting against other stimuli by recruiting more computational resources (Baars, 1988), or given its ability to elicit integrated information in the brain (Tononi & Edelman, 1998). These accounts would accommodate very well with categorization preceding conscious access: digitization offers a computational advantage to the representation, allowing it to win the competition for global broadcasting, or to trigger greater information integration. In the same lines, categorical perception effects can be observed in early stages of the perceptual analysis of the stimulus: around 200 ms after stimulus presentation during phoneme perception (Dehaene-Lambertz, 1997), as soon as 100 ms during color discrimination (Thierry et al., 2009), and on the N170 component in response to face stimuli (Campanella et al., 2000, 2002). These early stages are usually associated with unconscious responses of the perceptual systems. Thus, these observations support the hypothesis that in the correlation we report the categorization of information precedes consciousness.

Yet, the reciprocal link might be considered as well. Indeed, when the stimulus wins the competition and accesses the broadcasting resources of the "global workspace", then it can reach further computational resources and receive discrete processing from distant processors. Remarkably, these two causal directions are not mutually exclusive, and might actually combine together. That is, the more the stimulus receives discrete processing, the more it can access to the workspace resources, and in turn the more it receives further discrete processing from distant processors. One could envision that these reciprocal causal links support the "ignition" of a large network of brain regions observed empirically when the stimulus reaches consciousness (Dehaene, Changeux, Naccache, Sackur, & Sergent, 2006). To investigate further this issue, one could assess in a brain imaging experiment the relation between the activity of this fronto-parietal "workspace" network and whether perceptual regions, e.g. the fusiform face region which can respond to subliminal faces (Kouider et al., 2009), represent the stimulus in a discrete or analog manner.

As a methodological note, we would like to emphasize that the priming approach employed here offers the possibility to collect continuous data (response times, neural responses) in an indirect task that does not obviously lead to categorical effects. In our study participants were not instructed to categorize or to pay attention to the morphed primes. Thus, the non-linear effects in the supraliminal condition emerged from the specific characteristics of perceptual processing rather than task-related strategies or decision-based demands. Similarly, a recent fMRI experiment by Rothstein et al. (2005) used priming with morphed faces while participants were engaged in an irrelevant task, responding to the occurrence of an unrelated face that appeared on 15% of trials. In this study neural priming was found in the posterior inferior occipital gyrus, which was sensitive to any physical changes, and in the right fusiform gyrus (identified as the fusiform face area), which by contrast was specifically sensitive to identity changes and showed a categorical profile. Further work benefiting on this powerful combination of the priming method with brain imaging could investigate these linear and non-linear responses while varying the stimulus visibility.

In the present study we modulated the visibility of the primes by varying their duration (i.e., 43 ms vs. 300 ms) to investigate categorical processing under subliminal and supraliminal conditions. Future investigations of this issue could aim at manipulating perceptual awareness while maintaining constant the duration of the stimuli, or manipulating processing time and perceptual awareness orthogonally to disentangle their respective influence on the processing mode (linear vs. categorical). Interestingly, computational models based on attractor networks may capture the analog/digital dissociation observed here by relying solely on the amount of time available for processing the stimulus, which provides support for the hypothesis that discretization precedes perceptual awareness. Indeed, attractor networks simulations can successfully mimic the analog followed by all-or-none responses observed by cell recording from infero-temporal neurons in monkeys (Akrami, Liu, Treves, & Jagadeesh, 2009). The profile of priming in the present study can be described along these lines as well, by considering a network that will have identities of famous faces as attractors. In the short prime duration condition, the response to the prime would be less affected by attractor basins and reflect more gradually and more faithfully the stimulus characteristics, while in the long prime duration condition, the network would have time to converge towards one of its attractors, which corresponds to a discretization process, as the gradual information presented in the stimulus is then lost. Then, assuming that this activity at the end of the processing of the prime adds up with the response to the target, the model would produce linear priming effects with short prime durations, and non-linear effects with long prime durations. Importantly, the parameters of such an attractor model would include connectivity between units, the input signals it receives, and the processing time available, but not perceptual awareness.

To conclude, we acknowledge that further empirical studies are necessary to generalize the present result. Further research investigating the special link between discrete processing and perceptual awareness which is suggested by the present experimental work might also try to bridge the gap between an attractor network perspective and cognitive accounts of perceptual awareness.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.concog.2011.02.001.

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