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Spatial frequencies or emotional effects? A systematic measure of spatial frequencies for IAPS pictures by a discrete wavelet analysis

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Abstract

The influence of the emotional attributes of a visual scene on early perception processes remains a key question in contemporary affective neurosciences. The International Affective Picture System (IAPS; Lang et al., 2005) was developed to provide a set of standardized stimuli for experimental investigations of emotional processes. These stimuli have been widely used in brain activity investigations to study the influence of valence and/or arousal on visual processing. However, visual perception is strongly influenced by the physical properties of the images shown, especially their spatial frequency content, an aspect that has been unexpectedly neglected at large. In this study, we examine the complete set of IAPS with a discrete wavelet transform to highlight relations between the energy in different spatial frequencies and the emotional features of the pictures. Our results showed that these associations are weak when the complete dataset is considered, but for selected subsets of pictures, clear differences are present in both affective and spatial frequency content. The IAPS remains a powerful tool to explore emotional processing, but we strongly suggest that researchers use subsets of images that are controlled for the energy of their spatial frequencies when investigating emotional influence on visual processing.
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1. Introduction

The International Affective Picture System (IAPS; Lang et al., 2005), an internationally distributed and widely used set of colour photographs that depicts objects and scenes across a wide range of categories, was developed to provide a set of standardized stimuli for experimental investigations of emotional processes. These stimuli are frequently used (more than 100 citations listed in ScienceDirect® in 2006) in studies on brain activity to demonstrate the influence of differential valence and/or arousal levels on visual processing. Recently, several studies have demonstrated the influence of the emotional content of the pictures on various brain activities related to visual processing. For instance, using the event-related electrical activity of the brain, some authors (e.g. Schupp et al., 2003) showed that one of the earliest phases of visual processing (about 100 ms after stimulus onset) was differentially sensitive to neutral and emotional stimuli. Using functional imaging techniques (fMRI), other authors (e.g. Bermpohl et al., 2006) reported an increase in the activation of the primary visual areas (e.g. V1) when an emotional picture is perceived as compared with a neutral one. These examples illustrate that the emotional content of the IAPS pictures is thought to modulate brain activities related to primary and early visual processing in both the spatial and the temporal domain. However, whereas some physical properties of the pictures (e.g. size, mean luminance) are controlled in most studies using the IAPS, in too few studies have the variations in spatial frequency of those pictures been controlled for—a point that could be of particular importance.

One can expect that visual perception is strongly influenced by the physical properties of the images presented, in particular the spatial frequency content of the visual scene. The spatial frequency parameter reflects how rapidly a property changes in space. For instance, a commonly used form of visual stimulus consists of vertical bars where lightness varies according to a sinusoidal function. In this case, the spatial frequency of the stimulus is simply the frequency of the sinusoid used to generate the pattern. In general, stimuli with fine detail, including sharp

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edges, have more energy in the high spatial frequencies, whereas stimuli for which the properties change more slowly in space have more energy in lower frequencies. Spatial frequencies can be measured in cycles per image (c·image^{-1}) or in cycles per degree of visual angle (c·deg^{-1} or cpd). Note that, for a picture, the number of pixels defines a cycle, and the spatial frequency content of a visual scene perceived by an observer depends on the distance between the scene and the observer (Sowden and Schyns, 2006).

It is now well established that brain activity is influenced by the spatial frequency of a visual scene. For instance, the electrical activity of the brain (represented by event-related potentials [ERPs]) is highly dependent on the spatial frequency of the evoking stimulus in the 80- to 120-ms latency range (see Baas et al., 2002, for further details). Various amplitude and topographical effects have been observed as a function of the low (0.75 cpd) and the high (6 cpd) spatial frequency content of a stimulus at 90 ms (Kenemans et al., 2000). Moreover, using functional imaging techniques (fMRI), some authors have demonstrated that the primary visual areas are sensitive to spatial frequencies. Indeed, V1 activation is reduced for spatial frequencies above 4–6 cpd, whereas V2, V3 and VP activations are reduced at lower spatial frequencies (Singh et al., 2000). In summary, these studies demonstrate that the physical property of the picture in terms of spatial frequency strongly modulates the activity related to primary and early visual processing in both the spatial and the temporal domain.

These results raise the question of whether the emotional influences on visual processing observed using pictures taken from the IAPS might be confounded by the effect of the spatial frequency content of these pictures. This problem is of particular importance because the functional visual brain circuitry that conveys the frequency information is closely related and functionally linked to the circuitry that conveys the emotional information, at least for the early processes (Bar, 2003). In brief, the parvocellular pathway mainly transports the high spatial frequencies to the ventral visual cortices, whereas the magnocellular pathway mainly conveys the low frequency information of a visual scene via the dorsal parietal stream and connected subcortical regions. In this framework, it has been demonstrated that the magnocellular pathway projecting to the amygdala could convey fearful information of low-pass filtered faces (Vuilleumier et al., 2003). Moreover, Carretié et al. (2007) have recently demonstrated that low-pass filtered unpleasant pictures (not taken from the IAPS) elicited higher amplitudes than did low-pass filtered neutral pictures on an ERP component elicited 135 ms after the onset of the picture and originating from secondary visual areas. Because this difference was abolished when the stimuli were intact, the authors concluded that, at this stage of processing, the high spatial frequencies do not play a crucial role in emotional features processing. This study represents the first direct evidence of an interaction between the emotional content of complex natural scenes and their low spatial frequency content.

All the elements cited above highlight the necessity to control for spatial frequency content in order to avoid potential misattribution of effects to the emotional characteristics of the picture. To date, few authors have addressed the spatial frequency content of their visual material. Among them, Junghöfer et al. (2001) mentioned that the discrepancies they observed in the visual ERPs in response to checkboards varying either in brightness or spatial frequency were clearly different from those observed between neutral and emotional arousing pictures. These authors concluded that the affect discrimination of IAPS that they observed is independent of formal visual properties of the stimuli. More recently, the same authors used IAPS subsets of pictures controlled for their mean spatial frequency content (Junghöfer et al., 2006). However, even if this study constitutes one of the most rigorous in regard to the control of the stimuli, the mean spatial frequency of a picture could not be accurate enough, given that not all frequencies would be equally informative of the emotional content they convey (c.f. Carretié et al., 2007; Vuilleumier et al., 2003). Thus, for each picture, the estimation of the energy of the different spatial frequencies along the spectra is missing. Unfortunately, there has been no information available concerning the spatial frequency content of the IAPS stimuli. The aim of the present study is to analyse the complete set of IAPS items with a discrete wavelet transform. We propose (1) to examine to what extent affective ratings could be confounded with spatial frequencies by showing examples of picture selections with clear differences in both affective and spatial frequency content and (2) to provide researchers with systematic data to control for potential confounds.

2. Material and methods

2.1. Stimuli

Eight hundred and twenty-three colour pictures taken from the IAPS were transformed (using Photoshop™ v8.0 software) in order to obtain the greyscale version and the three RGB (red, green and blue) layers of 512 × 512 pixels (by changing the size of the picture if it was needed) from each original picture (see an example in Fig. 1). This decomposition was performed because colour and greyscale spatial frequency discrimination thresholds are not identical (e.g. Vimal, 2002).

2.2. Discrete wavelet analysis

Wavelets are mathematical functions that were developed by scientists in different fields to explore data in the frequency domain. By using these analyses, both small features (details, high spatial frequencies) and large features (low spatial frequencies) can be differentiated and studied separately. For each greyscale picture and RGB layer, a multi-resolution decomposition analysis was performed with Haar discrete bi-dimensional orthogonal wavelets (eight levels, Splus™ v7.0 software with S + Wavelet™ v2.0 package; see Bruce and Geo, 1996, for further information). In sum, discrete wavelet transform provides the most compact representation of the data, is very fast and is best suited for image processing (Mallat, 1999). Moreover, Haar wavelet functions are orthogonal, meaning that they have no overlap with each other (zero correlation) when computing the wavelet transform. Consequently, the energy of a particular frequency band is *a priori* independent from the other bands.

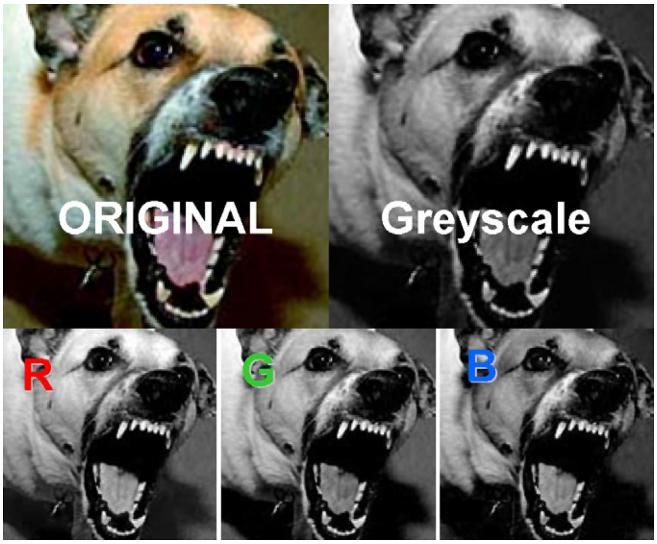

Fig. 1. Example of original picture (not taken from the IAPS for copyright reasons) together with its greyscale version and the three RGB layers. Note that colour information is lost in each layer, replaced by luminance variations.

Table 1
Characterization of the eight frequency bands analysed with the wavelet

<4 pixels/cycle band	High spatial frequencies
4–8 pixels/cycle band	
8–16 pixels/cycle band	
16–32 pixels/cycle band	
32–64 pixels/cycle band	
64–128 pixels/cycle band	
128–256 pixels/cycle band	
>256 pixels/cycle band	Low spatial frequencies

The principle of this analysis is represented in Fig. 2 for five levels of decomposition.

At each level (L1, L2, ...), the two-dimensional discrete wavelet transform leads to a decomposition of approximation coefficients into four coefficient matrices: the approximation at the following level (the smooth part, A) and the details in three directions (horizontal = hD, vertical = vD and diagonal = dD). For each decomposition matrix, the mean energy was then calculated for each of the eight frequency bands described in Table 1. This calculation was done by averaging the sum of the square values for the horizontal, vertical and diagonal coefficients obtained at each portion of the layer (i.e. one cycle × one cycle surface)[1].

2.3. Picture filtering and apparent contrast calculation

It is well established that human visual perceptions are most sensitive to the contrast for middle frequencies (5–10 cpd; e.g. Van Nes and Bouman, 1967) and quite insensitive to very low and very high frequencies. Therefore, in addition to the spatial frequency, the apparent contrast associated with each frequency band must be taken into account. To this effect, pictures were first filtered (using ImageJ v1.35 software) according to the spatial frequency bands analysed by the wavelet. Then, for each of these bands, the subjective/apparent contrast was obtained (ImageJ v1.35 software) by dividing the standard deviation of luminance values by the mean luminance of each filtered image (see Bex and Makous, 2002, for further details).

3. Results

One of our objectives was to provide researchers with information on the spatial frequency content of the IAPS. For each picture, we obtained 70 different measures corresponding to the energy and apparent contrast calculated for each frequency band and each type of layer (greyscale and RGB). The complete procedure, the spatial frequency results and the different codes needed to perform the analyses with Splus™ as well as with Matlab™ software are available at the following internet address: http://affectco.unige.ch/spatfreq. In order to obtain a primary evaluation as to whether the spatial frequency content of the pictures could predict their emotional content, we performed an exploratory regression strategy on the entire dataset. First, spatial frequencies lower than 8 c·image^{-1} (low spatial frequencies = LSF; <0.64 cpd in a 17-in., 800 × 600 pixel monitor at a distance of 1 m) and higher than 16 c·image^{-1} (high spatial frequencies = HSF; >1.28 cpd in a 17-in., 800 × 600 pixel monitor at a distance of 1 m) were analysed separately for each layer. The choice of these boundaries is based on preceding studies showing differential brain activity related to emotional expression presented on faces filtered with such parameters (Vuilleumier et al., 2003). Coefficients were *Z*-score transformed for inter-band comparability. Then, for each layer, we performed a series of linear and quadratic regressions, with the valence and the arousal rating values as criterion variables and the spatial frequency *Z*-scores and apparent contrast values as predictor variables. In sum, although several regression analyses reached significance, the determination coefficients that were associated with these analyses were all very weak ($R^2 \leq 0.018$). These analyses indicate that there is no important systematic relation between the emotional ratings and the spatial frequency content across the entire database, which could have called into question its use to investigate the interactions between emotional and visual processing.

However, in our opinion, a confound could occur when a significant statistical difference reported between groups or selections of pictures on emotional ratings (valence and/or arousal) is also observed with respect to their spatial frequency content. In the following sections, we present selections of pictures that could produce such a confound.

3.1. Examples of semantic categories

One experimental approach that uses the IAPS is to select specific categories of picture content (e.g. animals, faces, landscapes) in order to investigate the effect of specific categories on behavioural or cognitive indices. This approach has been used in a recent contribution (Mikels et al., 2005) showing the potential

[1] Formula: Energy for one portion $x = \mathrm{hc}^2 + \mathrm{vc}^2 + \mathrm{dc}^2$ where hc = horizontal coefficient, vc = vertical coefficient, dc = diagonal coefficient. Mean energy $X = (\sum_{(1-\mathrm{n})}(x)/n)$ where n: the number of the portion in the picture (depending on the size of the cycle).

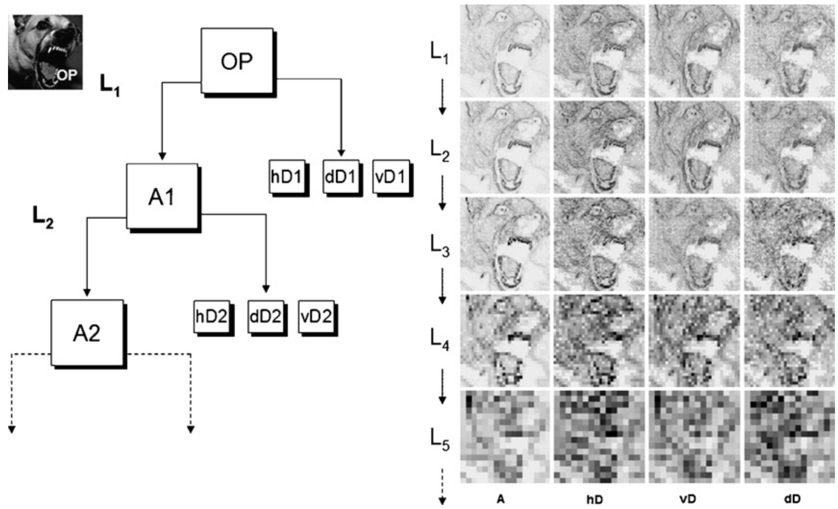

Fig. 2. Two-dimensional discrete wavelets decomposition principle and the resulting wavelet coefficients representations. OP = original picture, A = approximation, D = details, h = horizontal, d = diagonal, and v = vertical.

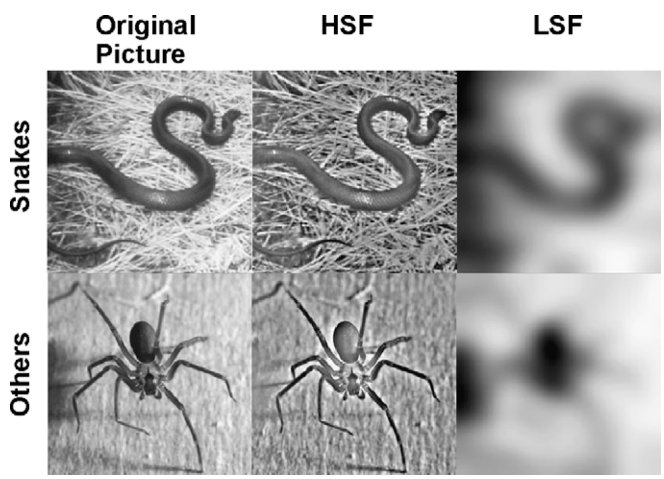

Fig. 3. Samples of two greyscale pictures filtered above 16 c·image^{-1} (HSF) and below 8 c·image^{-1} (LSF).

of these pictures for investigating discrete emotions by constituting semantically related emotional categories. For instance, let us imagine a study aimed at comparing reactivity to snakes as compared with other unpleasant animals.

Seventeen pictures of snakes and 17 pictures of other unpleasant or threatening animals[2] (e.g. spiders, squalls, beetles) were selected (see Fig. 3).

First, spatial frequencies lower than 8 c·image^{-1} (LSF) and higher than 16 c·image^{-1} (HSF) were analysed for the greyscale layer. Coefficients were *Z*-score transformed for inter-band comparability. A MANOVA was conducted (SPSS™ v.13) on valence, arousal, energy and apparent contrast at low and high spatial frequencies as dependent variables and on group of pictures (snakes versus other animals) as the within factor. The mean valence, arousal LSF and HSF energy calculated for the two groups of pictures (snakes versus others animals) are represented in Fig. 4A.

Even if there was no significant difference in the values of valence, arousal, energy of the LSF or contrast of high versus low spatial frequency pictures, the pictures of snakes contain significantly more energy in the high frequency band than do the pictures of other unpleasant animals [$F(1,32) = 4.54$; $p < 0.05$; $\eta^2 = 0.12$]. Consequently, the two groups of pictures specifically selected on the basis of a content category also differ in their physical properties. Thus, if significant differences in the activity of perceptual brain areas are reported between snakes and other animals, then it is difficult to decide whether it is an effect of content category or of spatial frequencies.

In the same vein, we decided to study such a semantic grouping in the pleasant domain. Because nudes or erotic pictures are often employed as pleasant stimuli, it would be interesting to know if these semantically restricted types of pictures differed in their spatial frequency content when they are compared with equally pleasant and arousing but non-erotic pictures. Twenty pictures of erotic couples and 20 pictures of other pleasant but less semantically restricted scenes[3] (e.g. skiers, pilots, plane) were selected in such a way that the two groups were as close as possible according to the valence [$F(1,38) = 3.16$; ns] and the arousal dimensions [$F(1,38) = 2.1$; ns]. We applied the same previously described procedure and analyses on LSF (i.e. <8 c·image^{-1}) and HSF (i.e. >16 c·image^{-1}). The mean valence, arousal LSF and HSF energy calculated for the two groups of pictures (erotic couples versus other pleasant pictures) are represented in Fig. 4B. Even if there was no significant difference in the values of valence or arousal, the pictures depicting erotic

[2] The IAPS identification numbers are as follows. Pictures of snakes: 1090, 1120, 1050, 1114, 1112, 1110, 1080, 1040, 1051, 1022, 1111, 1052, 1113, 1019, 1101, 1070, 1030. Other animals: 1275, 1201, 1274, 1270, 1302, 1301, 1303, 1930, 1932, 1230, 1205, 1280, 1220 1525, 1200, 1300, and 1240.

[3] The IAPS identification numbers are as follows. Erotic couples: 4669, 4683, 4664, 4800, 4672, 4652, 4666, 4810, 4653, 4658, 4659, 4670, 4656, 4676, 4677, 4689, 4690, 4680, 4650, and 4660. Other pleasant pictures: 1650, 2389, 5450, 5626, 7600, 8021, 8031, 8034, 8040, 8116, 8130, 8161, 8191, 8192, 8193, 8251, 8300, 8341, 8400, and 9156.

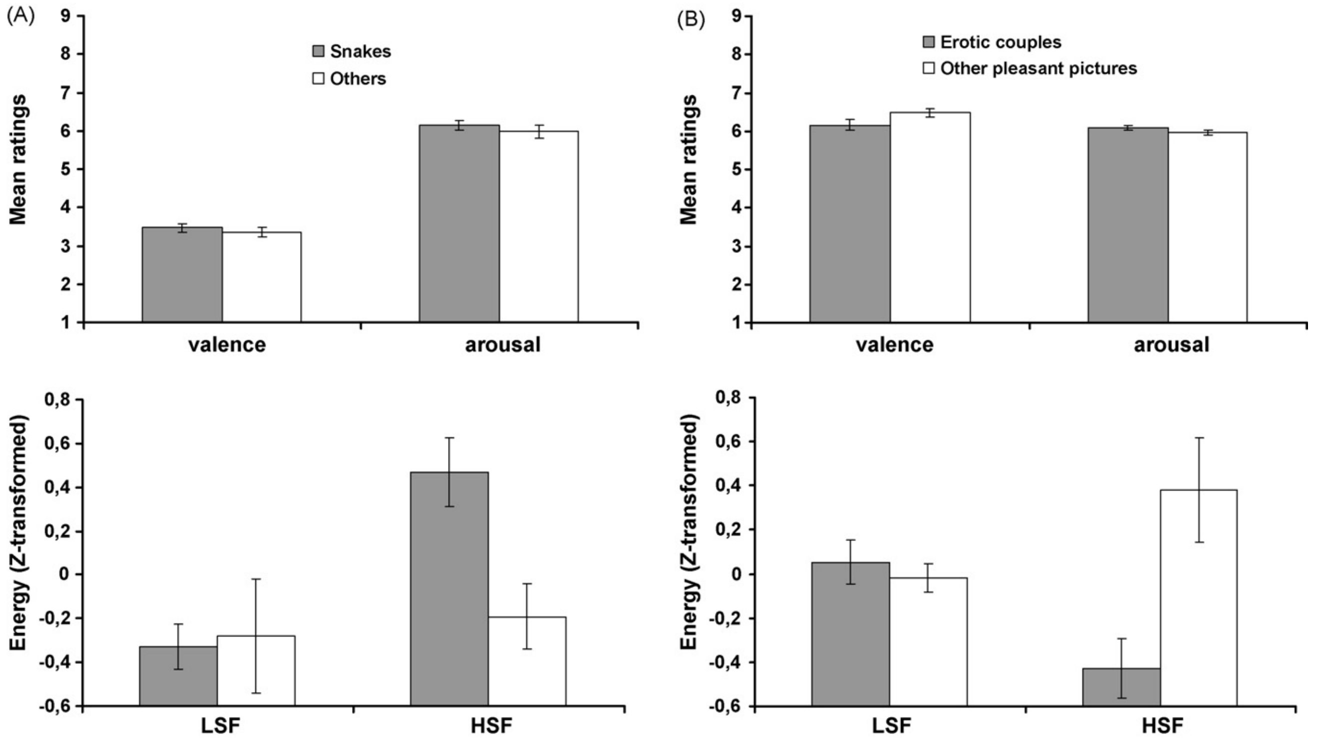

Fig. 4. Mean scores (±S.E.M.) of valence, arousal and *Z*-score transformed wavelet coefficients for the pictures of snakes *vs.* other animals (part A) and the erotic couples *vs.* other pleasant pictures (part B).

couples contain significantly less energy in the high frequency band than do the other selected pleasant scenes [$F(1,38) = 10.37$; $p < 0.01$; $\eta^2 = 0.21$]. Here again, the two groups of pictures specifically selected on the basis of category content are also different from a perceptual point of view. This point could be of particular importance when the objective of the study is to investigate the influence of the content category on the low-level sensory visual processing.

3.2. Transversal selection

One of the specificities of the IAPS pictures is that this large database includes content across a wide range of categories. Many researchers have selected their set of pictures according to this approach, and their selections are made as a function of valence and arousal ratings without considering systematically the existence of semantic categories across their selection. Thus, it is possible to create large sets of pictures, which represents a great advantage when the techniques used to record brain activity need to be associated with the presentation of a great number of stimuli (e.g. ERPs). Seventy-five greyscale pictures[4] were taken from the IAPS (25 unpleasant = U, 25 neutral = N and 25 pleasant = P; for an example, see Fig. 5).

The three groups of pictures were chosen so that they differed in valence [$F(2,72) = 335$; $p < 0.01$; $\eta^2 = 0.9$] and in arousal [$F(2,74) = 353$; $p < 0.01$; $\eta^2 = 0.91$], but the pleasant

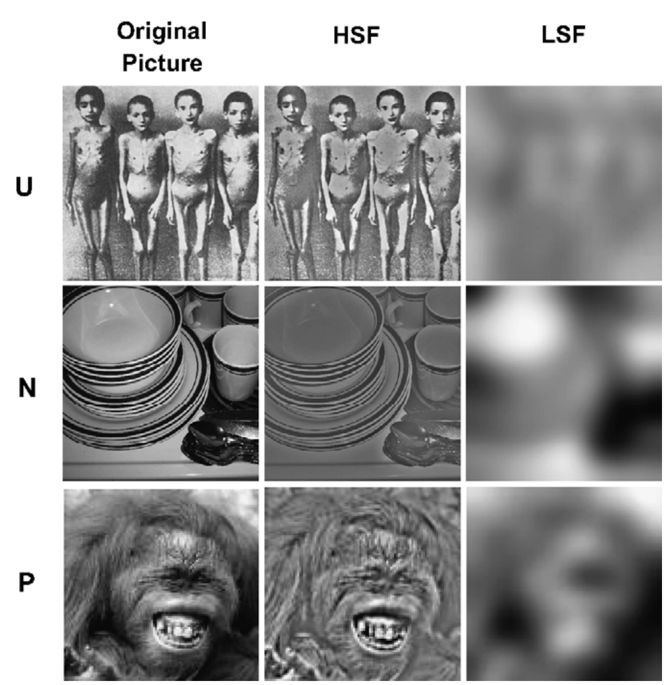

Fig. 5. Samples of three greyscale pictures (unpleasant = U, neutral = N and pleasant = P) filtered above 16 c·image^{-1} (HSF) and below 8 c·image^{-1} (LSF).

[4] The IAPS identification numbers are as follows. Unpleasant pictures: 1040, 1080, 1280, 1321, 1930, 2692, 2751, 3181, 3250, 3301, 4621, 6244, 6370, 6831, 7359, 8230, 9040, 9140, 9300, 9400, 9405, 9430, 9470, 9621, and 9911. Neutral pictures: 2190, 2221, 2381, 2499, 2570, 2580, 2840, 2870, 2980, 4250, 4605, 5510, 5530, 5533, 7002, 7031, 7041, 7050, 7090, 7160, 7175, 7185, 7234, 7491, and 9360. Pleasant pictures: 1811, 2352, 2352.1, 4503, 4530, 4537, 4561, 4599, 4607, 4608, 4626, 4681, 4690, 5460, 5628, 7260, 7289, 7481, 8033, 8130, 8185, 8220, 8340, 8501, and 9156.

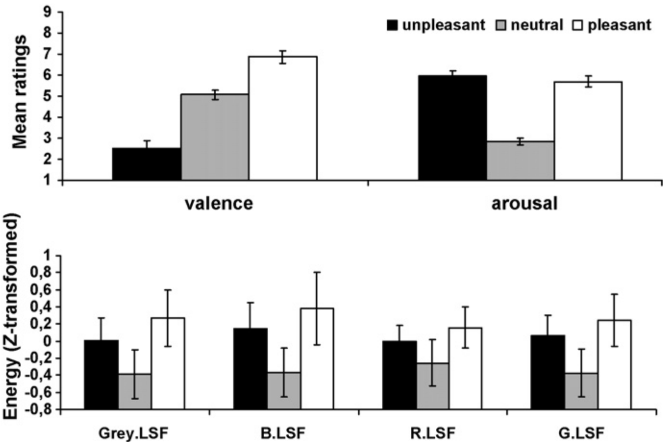

Fig. 6. Mean scores (±S.E.M.) of valence, arousal, and *Z*-score transformed wavelet coefficients (RGB and greyscale) for the three groups of pictures.

and unpleasant group did not differ significantly in the arousal dimension (post hoc Tuckey HSD test, $p > 0.05$). The mean values of valence and arousal are presented in Fig. 6. This pattern of arousing unpleasant and pleasant pictures contrasted with non-arousing neutral pictures is very frequently encountered in studies using the IAPS. Visual inspection of the content of the three subsets of pictures reveals that they all contain objects and scenes crossing different categories and it is *a priori* difficult to guess whether they differ in their spatial frequency content. Spatial frequencies lower than 8 c·image^{-1} (LSF) and higher than 16 c·image^{-1} (HSF) were analysed separately for each greyscale picture and each layer of colour (RGB). Coefficients were *Z*-score transformed for inter-band comparability. No consistent difference between the three groups was observed for the HSF. Results for the low frequency band are presented in Fig. 6.

In sum, the results show that the emotional pictures contained more energy in the low frequency band than did the neutral pictures not only for the greyscale layer, but also for the blue, the red and the green layers [$F_s(2,72) = 7.71$, 7.18, 5.09 and 7.88, $p_s < 0.001$, 0.001, 0.01, and 0.001, $\eta_s^2 =$ 0.17, 0.16, 0.12 and 0.18, respectively]. Moreover, there was no difference in the energy of the low spatial frequencies between the unpleasant and the pleasant pictures. This result means that there is a probable confound between the arousal dimension and the energy in low frequencies.

In the case of a difference observed in occipital activation or in visual ERP component amplitude for emotional pictures as compared with neutral pictures, there could be a clear confound between an arousal effect and a spatial frequency effect.

4. Discussion

The two aims of this analysis of the complete set of IAPS pictures with a discrete wavelet transform were (1) to provide researchers with systematic data to control for potential confounds and (2) to present examples of picture selections with clear differences in both affective and spatial frequency content. Our analysis has shown that, even if there is no systematic association between the emotional and the spatial frequency content across the whole database, it is possible to select groups of pictures that differ not only in valence and/or in arousal, but also in the energy of their spatial frequencies. This emphasizes the benefit of checking the spatial frequencies of the pictures used when the modulation of visual processing by emotion is the focus of interest.

In particular, the transversal selection we have presented shows a bias with higher energy in the low frequency bands for emotional pictures as compared with neutral pictures. We believe that checking the low frequency content of the experimental material is of particular importance because a growing number of data reveal the close functional relationship between the extraction of low frequencies and emotional processing of faces (Vuilleumier et al., 2003; Pourtois et al., 2005) or natural scenes (Carretié et al., 2007). Moreover, concerning the hemispheric dominance associated with spatial frequency processing, there is a right hemisphere superiority in low spatial frequency processing, whereas a left hemisphere superiority is observed for high frequencies (Peyrin et al., 2003). In the emotional domain, two influential hypotheses exist (reviewed by Davidson, 1995): the right hemisphere hypothesis postulates right hemisphere dominance in emotional processing independent of the valence dimension; the valence hypothesis proposes that unpleasant emotions are mainly processed in the right frontal areas and pleasant emotions are mainly processed in the left frontal areas. Once again, one could speculate that an observed hemispheric dominance in emotional processing in response to complex natural scenes or faces could be due to a difference in the spatial frequency of the material.

One major strategy that prevents an individual from being confronted with the complex interactions between spatial frequencies and emotional content is to use similar pictures that differ only in an emotionally relevant feature but that are supposed to be identical in all other aspects. This very strict approach has already been used by Kayser et al. in several studies (e.g. Kayser et al., 1997, 2000) using pictures depicting patients with dermatological diseases before (unpleasant) and after (neutral) they were treated. Indeed, each negative stimulus possesses its own control corresponding to the cured situation. In this context, the researchers were able to separate ERP components associated with early visual processing that did not vary as a function of the emotional content of the picture, whereas other later components were enhanced in response to the unpleasant pictures, and especially over the right parietal regions. Although this procedure does not completely abolish the perceptual differences between emotional and neutral pictures, it represents a very elegant strategy to reduce the influence of spatial frequency on emotional processing.

In summary, the results of this study showed an absence of any strong and systematic correlations between the valence and/or arousal attributes of IAPS pictures and their spatial frequency content when the whole database is analysed. Thus, in this regard, the database as a whole is not biased. However, the IAPS is rarely used in its entirety; rather, studies typically rely on the selection of picture subsets. In this case, and particularly when the investigation concerns the influence of the emotional attributes of a picture on early visual processing, our results demonstrate the necessity of controlling the spatial frequency content of the subsets. Further investigations are needed to evaluate the relative contribution of spatial frequency differences in EEG and fMRI signals. Moreover, this result indicates the necessity of controlling the spatial frequency content of material other than the IAPS. Thus, the methodology used here should be generalized to other stimulus databases.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jneumeth.2007.05.030.

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