

Spatial frequency impacts perceptual and attentional ERP components across cultures

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ABSTRACT

Culture impacts visual perception in several ways. To identify stages of perceptual processing that differ between cultures, we used electroencephalography measures of perceptual and attentional responses to *simple* visual stimuli. Gabor patches of higher or lower spatial frequency were presented at high contrast to 25 American and 31 East Asian participants while they were watching for the onset of an infrequent, oddball stimulus. Region of interest and mass univariate analyses assessed how cultural background and stimuli spatial frequency affected the visual evoked response potentials. Across both groups, the Gabor of lower spatial frequency produced stronger evoked response potentials in the anterior N1 and P3 than did the higher frequency Gabor. The mass univariate analyses also revealed effects of spatial frequency, including a frontal negativity around 150 ms and a widespread posterior positivity around 300 ms. The effects of spatial frequency generally differed little across cultures; although there was some evidence for cultural differences in the P3 response to different frequencies at the Pz electrode, this effect did not emerge in the mass univariate analyses. We discuss these results in relation to those from previous studies, and explore the potential advantages of mass univariate analyses for cultural neuroscience.

1. Introduction

Cross-cultural differences have been demonstrated for several higher-level cognitive processes, including culture-related strategies for how information is organized and remembered (Gutchess, Yoon, et al., 2006; Ji, Zhang, & Nisbett, 2004). These differences are often attributed to differences in social orientation, such as the values and sources of motivation associated with how one conceptualizes of the self. Specifically, the attribution is whether self is conceptualized as unique and independent (Westerners) or as connected to and interdependent with others (Easterners) (Markus & Kitayama, 1991; Varnum, Grossmann, Kitayama, & Nisbett, 2010). Analogous accounts of cultural differences have been reported for a number of visual tasks, like face perception (Estéphan et al., 2018; Miellet, Vizioli, He, Zhou, & Caldara, 2013; Tardif et al., 2017), which can be considered high-level within the hierarchy of visual processing (Jennings & Martinovic, 2014). In particular, when it comes to face perception individuals from different cultural backgrounds are free to prioritize different facial features or in how they deploy attention over space (Blais et al., 2021; see also Im et al., 2017).

For example, compared to Westerners, Easterners tend to fixate on the center of the face and draw on other information from peripheral vision, which is consistent with the idea that Easterners tend to spread visual attention more broadly than Westerners (as reviewed by Blais et al., 2021).

Of course, faces are not the only visual stimuli whose complex structure allows for cultural variation in processing strategy. For example, McKone and colleagues (2010) investigated cultural variation in the salience of different ranges of spatial frequency. Specifically, they focused on the differences in the use of global, spatially coarse information (lower spatial frequency, LSF), corresponding to overall scene structure, and local (higher spatial frequency, HSF) information, corresponding to sharp edges and fine details. They reported that when allowed a choice of which kind of information to use, Easterners prioritized global information more than Westerners did (although note that cultural differences in Navon letter processing are not always found, e.g., Hakim et al., 2017). This conclusion was based on reaction times to Navon figures (Navon, 1977), which are large letters made up of smaller letters (e.g., a large E composed of small Vs). To compare attention to

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global vs. local information, this task compares trials in which the target stimulus is defined locally (by the smaller letters, corresponding to high spatial frequency) rather than globally (the large, composite letter, corresponding to low spatial frequency) (Shulman & Wilson, 1987). These cultural differences in responding to Navon figures (McKone et al., 2010) seemed to be consistent with previous studies of cultural differences in the prioritization of central objects in a scene over more global, contextual information. That result has been confirmed using a variety of behavioral measures, such as memory (Masuda & Nisbett, 2001) and eye tracking (Chua, Boland, & Nisbett, 2005), as well as neural ones (Goh et al., 2007; Gutchess, Welsh, Boduroglu, & Park, 2006).

Behavioral studies of face processing converge with findings of cultural differences in response to Navon figures and scene processing. They all suggest that Easterners tend to use low spatial frequencies, associated with coarser, more global information, whereas Westerners tend to use high spatial frequencies, associated with fine details and more local information (Blais, Jack, Scheepers, Fiset, & Caldara, 2008; Rodger, Kelly, Blais, and Caldara, 2010; Tardif, Fiset, Zhang, Estephan, Cai, Luo, Sun, Gosselin, & Blais, 2017). These results have been extended by examining eye movements (Kelly, Miellet, & Caldara, 2010; Miellet, Vizioli, He, Zhou, & Caldara, 2013) and measuring the time course of effects (Estephan, Fiset, Saumure, Plouffe-Demers, Zhang, Sun, & Blais, 2018).

Several investigations of potential cultural influences on perception have worked with spatially filtered faces or with test objects presented on visually complex, realistic backgrounds. These complex stimuli contain a range of spatial frequencies, multiple distinct parts, and may engage a host of brain regions reflecting face or stimulus-specific processes. Furthermore, much of the cultural research using faces as visual stimuli has used judgments of emotion expressions, which has limited generalizability to other processes and types of stimuli (Jack, & Schyns, 2017; Jack, Blais, Scheepers, Schyns, & Caldara, 2009; Jack, Caldara, & Schyns, 2012; Jack, Garrod, Caldara, & Schyns, 2012; Suzuki, Goh, Hebrank, Sutton, Jenkins, Flicker, 2011).

Because low-level visual processes, which operate on elementary features like orientation, color, luminance, or motion, tend to be automatic, involuntary, and resistant to being overridden by higher-level processes (Firestone & Scholl, 2016), we wondered about possible limits to culture's penetration of perceptual processes. In particular, would we see cultural differences in a task that minimized opportunities for culture-related strategies, such as differences in selective attention, and focused, instead, on early stages of visual processing? To that end, we used a simple perceptual task together with simple stimuli, each comprising a narrow band of spatial frequencies. Importantly, the task did not require participants to make any overt behavioral responses to the variable spatial frequency stimuli. We used EEG markers of visual and attentional processes to compare Easterners' and Westerners' responses to high and low spatial frequency stimuli. Participants saw but made no behavioral response to the stimuli of different spatial frequencies; they only had to make a speeded response to the intermittent, unpredictable presentation of a probe stimulus. The spatial frequency stimuli were high-contrast Gabor patches, Gaussian windowed sinusoidal luminance distributions (Kovacs & Julesz, 1994). The use of Gabor patches, which can evoke strong activity in the primary visual cortex, allowed us to manipulate spatial frequency in order to directly test cross-cultural differences in low-level visual perception. We should note that a previous study found no evidence of cultural differences when the researchers used sinusoidal gratings to compare the contrast sensitivity functions of Easterners and Westerners (Tardif et al., 2017). However, stimuli in that study were presented near the threshold of detectability, and so were just barely visible. As a result, the study may have masked cultural differences that could have been revealed with clearly visible, super-threshold stimuli like the ones we used, which more closely resemble what would be encountered in everyday visual situations. Additionally, in that study, participants made behavioral responses to the stimuli of interest, while in our study participants observed the

stimuli without making a behavioral response, responding only to the intermittent probe stimulus.

To build on prior behavioral demonstrations of cultural differences in the salience of high versus low spatial frequency information (e.g., Miellet, 2013; Blais et al., 2008; Estephan et al., 2018), we measured event-related brain potentials (ERPs). ERPs arise from the synchronous activities of neuronal populations engaged in specific processing and are time locked to stimulus events. Their high temporal resolution reveals the time course of specific neural activation (Luck, 2014). Early ERP components, such as P1 and N1, are sensitive to a stimulus' spatial frequency content (De Cesare, Mastroia, & Codispoti, 2013; Ellemberg, Hammarrenger, Lepore, Roy, & Guillemot, 2001; Hansen, Jacques, Johnson, & Ellemberg, 2011; Roeber & Schroger, 2004), but also reflect effects of attention (Luck et al., 1994), including attention to particular spatial frequency bands (Martinez, Di Russo, Anillo-Vento, & Hillyard, 2001). A number of studies have used ERPs to examine neural mechanisms underlying global versus local processing of compound stimuli. For example, one study reported an enhanced occipital P1 wave when participants responded to local rather than global stimuli (Han, He, & Woods, 2000), whereas in another study LSF information evoked a larger P1 wave than HSF information (Tian, Wang, Xia, Zhao, Xu, & He, 2018).

Few studies have used measures of neural activity to investigate cultural differences. One, using a variant of Navon figures (Navon, 1977), Lao, Vizioli, & Caldara's (2013) ERP data showed that culture modulates individuals' early sensitivity to global and local shape categorization such that the P1 was sensitive to global congruency for Easterners but not Westerners. Later components between 200 and 350 ms established that both groups differed in their response to global vs local information at different time points. Easterners, but not Westerners, exhibited a greater response to local than global congruent information at a right centroparietal peak at 236 ms. Other peaks had larger differences for Westerners than Easterners, with Westerners showing larger responses to global than local at a peak at 273 ms over center-parietal electrodes and to local than global at a peak at 312 ms at electrode C5. Our focus on these components is in line with our prior fMRI research that identified cross-cultural differences in V2, an intermediate visual region (Ksander, Paige, Johndro, & Gutchess, 2018). Single-unit recording and fMRI data indicate that the region is sensitive to texture (Movshon & Simoncelli, 2014), or organization within a scene, which makes it a candidate region to respond to different spatial frequencies. However, no previous fMRI or ERP studies have tested how culture shapes individuals' preferential processing of different spatial frequencies using basic visual stimuli such as Gabor patches. Based on previous studies, we predicted that the P1 and N1 components would reflect the salience of HSF information for Westerners and the salience of LSF information for Easterners, indexing cultural differences in the later stages of visual perception.

In addition to perceptual processes, indexed by components such as the P1 and N1, it is possible that cultures may differ in attentional processes. Experience focusing on particular spatial frequencies in natural settings over time could bias attention, shaping the salience of or expectations for particular spatial frequencies. These attentional processes are indexed by the P3 component (Noyce & Sekuler, 2014). The P3 also exhibits differential sensitivity to high and low spatial frequencies, although the direction of the effects varies across studies. Specifically, a rapid serial visual presentation task with emotional faces as stimuli yielded a stronger P3 response to high than low spatial frequency information (Tian et al., 2018). In contrast, a Navon detection task induced a larger P3 response to global than local attention (Proverbio, Minniti, & Zani, 1998). These diverging findings likely reflect the sensitivity of this component to task features and expectations. In terms of cultural differences in the P3 response, two previous studies used paradigms focused on oddball detection. Although participants from Western European backgrounds had larger P3 responses to target events compared to East Asian Americans, the distinct P3 component to novel

events was larger for Easterners than Westerners, reflecting different sensitivity across cultures to contextual deviance (Lewis, Goto, & Kong, 2008). In another study, Easterners exhibited a larger P3 to both targets and novel stimuli than Westerners (Wang, Umla-Runge, Hofmann, Ferdinand, & Chan, 2014). Taken together these results indicate different expectancies across cultures, which could extend to greater P3 amplitudes when cultural groups perceive their preferred spatial frequencies in our task.

Because there is so little cross-cultural research on visual perception and attention, particularly using EEG, there is a paucity of results from which hypotheses could be derived. Thus, in addition to testing for cultural differences in ERP components reflecting visual perception (P1, N1) and attentional processes such as salience and expectations (P3), we also conducted an exploratory mass univariate analysis (Fields, & Kuperberg, 2020). With appropriate statistical correction for multiple comparisons, whole-brain analyses that identify time windows and electrodes that differ across cultural groups and spatial frequencies is advantageous, particularly given the youth of the field of cultural neuroscience. Beyond focusing on only the components in which we hypothesized we would find cultural differences, the whole brain approach allowed for the potential identification of additional components, which would inform future work.

2. Method

2.1. Participants

Based on power analyses from our behavioral pilot data (see [Supplementary Materials](#)) and ERP effects from the literature that examined relevant cultural differences (Estephan et al., 2018) and effects of spatial frequency (De Cesare et al., 2013; Tian et al., 2018), we *a priori* targeted samples of 30 for each cultural group. Estimated effect sizes (Cohen's *f*) ranged from 0.33 to 1.05, indicating at least 22 participants were needed to detect effects. Our total intended sample size exceeded these estimates, increasing the validity and generalizability of results by reducing the effects of outliers, as well as collecting reliable estimates by including many trials. However, when data collection was paused due to the COVID-19 pandemic, we decided to halt data collection and analyze the samples that we had at that time, which included a smaller sample of Americans.

A sample of 26 Westerners and 35 Easterners was recruited from Brandeis University. Data from five participants were excluded from analyses due to excessive artifacts (>35% of trials). The final sample consisted of 25 Westerners¹ (Mean age = 20.89, SD = 2.41; age range = 18–27, 10 male) and 31 Easterners (Mean age = 23.14, SD = 3.50; age range = 18–31, 14 male). Western participants were native English speakers from the U.S, not of Asian ethnicity, and had lived outside the U.S. for <2 years. Eastern participants were native to an East or Southeast Asian country (29 Chinese, 1 Taiwanese, 1 Vietnamese), and were recruited for having lived in the U.S. for <5 years (*M* = 2.57, *SD* = 2.02; in actuality, 3 participants reported being in the US for 6–8 years - longer than our criterion) and spoke fluent English. All participants had normal vision, based on performance on the ETDRS Test (Bailey & Lovie, 1976) and the Mars Letter Contrast Sensitivity Test (Dougherty, Flom & Bullimore, 2005), and had no history of neurological disorders. They provided written informed consent, and the study was conducted with approval from the Brandeis University Institutional Review Board.

2.2. Stimuli

Stimuli were Gabor patches, vertically oriented sinusoidal gratings windowed by a Gaussian function 1.7° half-width at half height. Spatial frequencies of the Gabor patches were either 1 cycle per degree (cpd),

the lower frequency stimulus, or 4 cpd, the higher frequency stimulus. For each trial, 4° x 4° Gabor patches were randomly presented on either the left or right side of the screen, with the center of the presented patch located 10.6° from the fixation cross. Fig. 1 shows the stimuli for the five trial types. Panels A-D show the spatial frequency-related stimuli. One of the two spatial frequency stimuli were randomly presented on 89% of the trials, with either spatial frequency occurring approximately evenly either to the left or right of the fixation mark. To maintain participants' vigilance despite the absence of behavioral responses to the Gabors, an oddball task was introduced on 11% of the trials (stimulus shown in Fig. 1, Panel E). On such trials, a small red disc of 0.5-degree angular size was presented for 0.1 s just below the fixation mark. the oddball disc was located 1° below the fixation cross, which was at the center of the screen. The contrast of both the Gabor stimuli and the oddball target was 0.5 across all the trials. Contrast and spatial frequencies were selected based on behavioral pilot data (see [Supplemental Materials](#)).

2.3. Procedure

When participants arrived in the lab, they first provided informed consent and completed demographics questionnaires. Then, participants were seated in a comfortable chair, and positioned to use a chinrest 60 cm away from the monitor. After the EEG set-up was completed (detailed below), participants were instructed on the task, completed several rounds of practice trials, and then started the task.

Participants were asked to stare at a fixation cross at the center of a uniform grey screen throughout the task. They were instructed to use peripheral vision to monitor for the onset of a red disc, to which they should press the spacebar as quickly as possible; this oddball was used to assess vigilance to the task. Either a Gabor patch or the probe, oddball disc flashed on the screen for 100 ms, with SOAs randomly varying from 1000 to 2000 ms, determined using a random number function. An auditory tone indicated the onset of each trials. Gabor patches were presented eight times more frequently than the red disc, which qualified the detection of the infrequently presented red disc as an oddball task (Squires, Squires, & Hillyard, 1975). In total, each participant completed 405 trials including 45 trials with the oddball and 360 trials with Gabor patches (half HSF and half LSF Gabor).

2.4. ERP recording and processing

The electroencephalogram EEG was continuously recorded using a BioSemi Active Two system and ActiView EEG acquisition software (more info on the website <http://www.biosemi.com/>). EEG signals were recorded from 32 Ag/AgCl electrodes in an ActiveTwo standard elastic cap, selected for the size of each participant's head. Electrodes were placed according to the international 10–20 system. In addition, two electrodes located at mastoids were used as reference. Eye blinks were monitored with electrodes located below the left eye and above the right eye. The sampling rate was 512 Hz.

Data processing and analysis was conducted in EEGLAB (Delorme & Makeig, 2004) and ERPLAB (Lopez-Calderon & Luck, 2014) running in Matlab 2016b. The EEG data were first referenced to the average of the mastoid electrodes, and then high pass filtered by a second order Butterworth IIR filter with half amplitude cutoff at 0.1 Hz. Then, segments from 200 ms before to 800 ms after stimulus onset were extracted.

Next, we conducted an independent component analysis (ICA). For this purpose, the mean voltage was temporarily removed from each segment at all the electrodes. Via visual inspection, trials with significant artifacts that were not neural, ocular or muscular were excluded from the data used to learn ICA weights. Using the extended infomax algorithm, independent components were calculated and those corresponding to eye blinks and saccades were manually identified and removed. On average, for each participant two independent components were linked to blinks or saccades.

After removing the independent components, all segments were re-

¹ Demographics data are missing for one American participant.

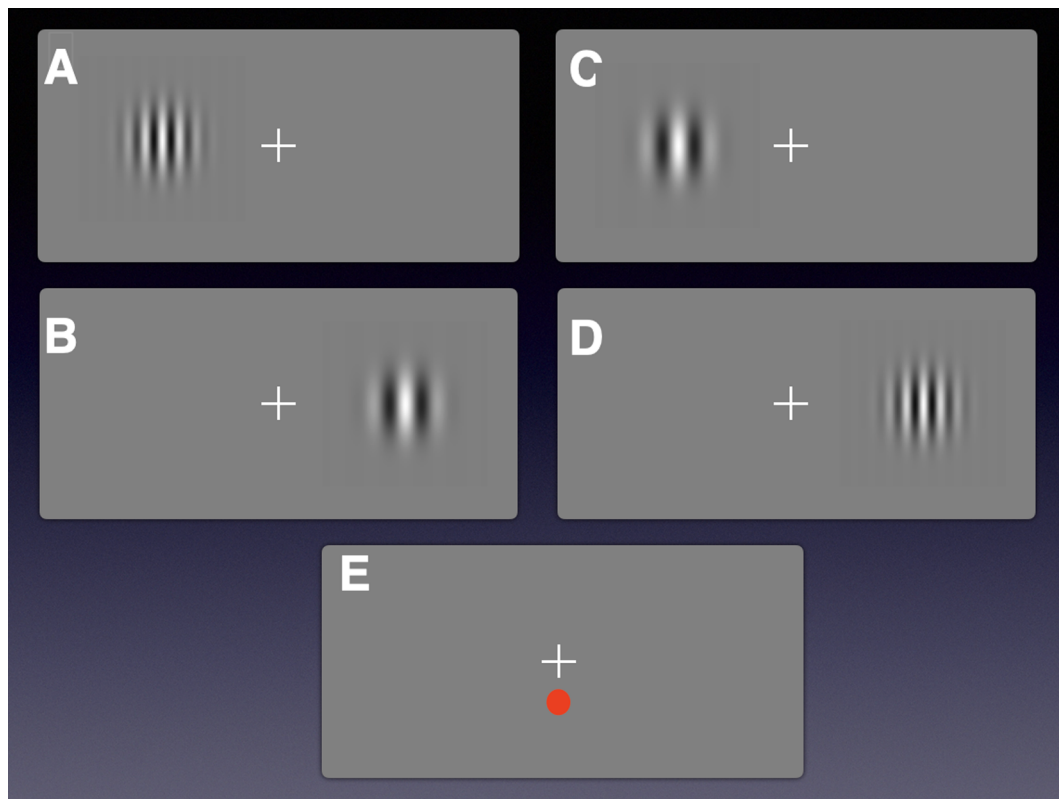


Fig. 1. Examples of Gabor patches of 4 cpd (panels A and D) and 1 cpd (panels B and C) presented to the left or right, and the oddball stimulus (panel E). Gabor patches were presented on the left or right side of the screen. The oddball stimulus, the red disc, appeared on only 11% of the trials. Note that these images are not to scale, but serve only as illustrations of the types of stimuli.

baselined to the pre-stimulus period. After that, we applied a combination of algorithms implemented in ERPLAB to identify trials with remaining artifacts and marked them for rejection². Trials with ocular artifacts in the -50 to 150 ms time window were rejected even if they were corrected by ICA because the stimulus presentation in this study is so brief that saccades or eyes being closed during the period would contaminate neural activity. After excluding five participants with excessive artifacts ($>35\%$ of trials), overall rejection rates ranged from 0.8% to 23.1% across participants with an average of 8% . The remaining ERPs to each type of stimuli were averaged across trials. Prior to analyses, the ERPs were low pass filtered with a cut-off at 30 Hz.

2.5. Analytic plan

To examine components predicted a priori to differ by culture, we

² We used the moving window peak-to-peak function (the difference between the most positive and most negative voltages within a window) and the step function (the difference between the mean voltage from the first half and second half of a window) as implemented in ERPLAB (<https://github.com/lucklab/erplab/wiki/Artifact-Detection-in-Epoched-Data>). A peak-to-peak function was applied to the difference between a forehead channel (Fp1, or Fp2 if Fp1 showed a lot of non-ocular noise) and the electrode under the left eye in 200 ms windows with a threshold around 75 μV to detect blinks. Step functions were applied in both 400 ms (to detect brief deflections) and 1000 ms (to detect slow drift) time windows at all channels with thresholds around 55 μV . Finally, a peak-to-peak function was applied in 400 ms time windows at all channels with a high voltage threshold (~ 300 μV) to detect particularly large EMG and other artifacts not picked up by the step function. Precise thresholds were sometimes adjusted for individual subjects' data based on visual inspection, but applied equally to all trials (and thus all conditions) for each subject (Luck, 2014, p. 191).

analyzed the P1, posterior N1, anterior N1, and P3 components. Based on existing literature with similar paradigms, we defined P1 as the most positive peak in 70 ms to 120 ms (De Cesare, Mastria, & Codispoti, 2013; Lao, Vizioli, & Caldara, 2013), and N1 as the most negative peak in 120 ms to 200 ms (Baas et al., 2002; Roeber et al., 2004; Zhang, Cong, Song, & Yu, 2013). For both P1 and posterior N1, we selected electrodes O1, O2, and Oz (Luck, 1994). For anterior N1, we chose F3, F4, Fz, C3, C4 and Cz (Luck 1994). For P3, we defined it as the most positive peak in 300 to 500 ms and analyzed it at Pz, and compared it with the peak at Fz and Cz (Noyce et al., 2014; Wang, Umla-Runge, Hofmann, Ferdinand, & Chan, 2014). Analyses of these components were pre-registered: <https://osf.io/2fyw8/>.

For each component, we calculated an ANOVA with spatial frequency (LSF, HSF) as a within-participant factor and cultural background (Eastern or Western) as a between-participants factor. Analyses were conducted in R (R Core Team, 2014) using the afex package (Singmann et al., 2021). The LSF condition corresponded to Gabor patches of 1 cpd (cycles per degree); the HSF condition corresponded to Gabor patches of 4 cpd. For all effects with more than one degree of freedom in the numerator, the Greenhouse-Geisser correction was applied to the degrees of freedom. Confidence intervals (95% CI) are included for null effects.

In addition to the pre-registered analyses, we used a complementary data-driven, non-parametric clustering approach. This allowed for the identification of time windows and electrodes that differed across cultural groups and spatial frequencies using the Mass Univariate Toolbox (Groppe, Urbach, & Kutas, 2011) and Factorial Mass Univariate Toolbox (Fields, & Kuperberg, 2020).

3. Results

3.1. Behavioral: Performance of target detection

As explained earlier, participants' responses to the onset of the intermittent oddball stimulus were used to verify participants' focus on the task. Overall, responses to the infrequent, oddball target were fast (mean across both groups ~ 400 ms) and participants failed to respond to the oddball on only one percent of all trials, a value that did not differ across spatial frequencies. Mean reaction time and detection rate are shown in Table 1. Reaction times did not differ between Easterners and Westerners, $t(54) = 0.37$, $p = .71$, $d = 0.35$.

3.1.1. ERP components - overview

As explained earlier, we predicted that Westerners would show relatively larger ERP responses to HSF Gabors, and Easterners would have relatively larger ERP responses to LSF Gabors. We hypothesized that cultural differences would be reflected in ERP components related to perception (P1, N1) and attention (P3). We conducted two-way mixed ANOVAs for spatial frequency (HSF and LSF) $\times$ cultural background (Eastern and Western) on the P1, N1 and P3 components.

3.1.2. ERP components - P1 and N1

For the P1 component, there was not a significant main effect of culture ($F(1, 54) = 1.56$, $p = .21$, $\eta^2_G = 0.018$, $CI = (-0.141, 0.607)$) or spatial frequency ($F(1, 54) = 0.28$, $p = .60$, $\eta^2_G = 0.002$, $CI = (-0.206, 0.355)$) or an interaction ($F(1, 54) = 0.24$, $p = .63$, $\eta^2_G = 0.002$, $CI = (-0.711, 0.438)$), as shown in Fig. 2. For the posterior N1, also depicted in Fig. 2, there was a significant main effect of culture ($F(1, 54) = 4.97$, $p = .03$, $\eta^2_G = 0.064$) such that the posterior N1 component was greater (more negative) for Easterners than for Westerners. However, there was no main effect of spatial frequency ($F(1, 54) = 1.80$, $p = .18$, $\eta^2_G = 0.009$, $CI = (-0.544, 0.107)$), nor was there a significant interaction between culture and frequency ($F(1, 54) = 0$, $p = .95$, $\eta^2_G < 0.001$, $CI = (-0.631, 0.670)$). Moreover, the overall topography of the components failed to show the expected pattern (e.g., as seen in Fig. 2, the component in the P1 window is negative-going and the component in the N1 window is positive-going).

For the anterior N1, although there was not a significant main effect of culture ($F(1, 54) = 0.44$, $p = .51$, $\eta^2_G = 0.006$, $CI = (-0.460, 0.911)$) or significant interaction between culture and spatial frequency ($F(1, 54) = 1.41$, $p = .24$, $\eta^2_G = 0.005$, $CI = (-1.060, 0.262)$), there was a main effect of spatial frequency, $F(1, 54) = 38.91$, $p < .001$ ³, $\eta^2_G = 0.123$. As Fig. 2 shows, the anterior N1 component was greater (more negative) for low than high spatial frequency stimuli. This result indicated that the N1 component was sensitive to a stimulus' spatial frequency content (Roeber, & Schröger, 2004), and could also reflect effects of attention (Luck, Hillyard, Mouloua, Woldorff, Clark, & Hawkins, 1994). Previous work substantiates the early neural response to detecting and making decisions about visual information (Thorpe, Fize, & Marlot, 1996); the

greater N1 response to the low spatial frequency stimuli supports the idea that they are faster to detect than the high spatial frequency stimuli.

3.1.3. ERP components - P3

For the P3 component at Pz, there was no significant main effect of culture, $F(1, 54) = 0.27$, $p = 0.61$, $\eta^2_G = 0.004$, $CI = (-2.101, 1.242)$, but there was a main effect of frequency $F(1, 54) = 13.06$, $p < 0.01$, $\eta^2_G = 0.019$, and a significant interaction between frequency and culture, $F(1, 54) = 4.32$, $p = .042$, $\eta^2_G = 0.007$. Easterners showed numerically higher average peak amplitude for HSF than Westerners (Easterners: $M = 7.06$, $SD = 3.49$; Westerners: $M = 6.11$, $SD = 3.11$), although the LSF was more comparable across the groups (Easterners: $M = 7.44$, $SD = 3.22$; Westerners $M = 7.53$, $SD = 3.06$). This pattern differed somewhat from the grand averaged ERPs displayed in Fig. 2 where it appears that the Western LSF response was slightly weaker than Eastern LSF for P3 on Pz. The reason why they differed was that the peak, used in the analyses, was at a different time point for each participant, whereas the peak of the grand mean reflects the average taken across all participants at the same time point (see Luck, 2014, pp. 284-291). We expanded the analysis of P3 to test it across three midline channels (Fz, Cz, Pz): there was a main effect of frequency $F(1, 54) = 4.05$, $p = 0.049$, $\eta^2_G = 0.007$ and a main effect of culture at Fz for P3, $F(1, 54) = 5.96$, $p = 0.018$, $\eta^2_G = 0.091$. A mixed ANOVA with factors of Culture (Eastern, Western) $\times$ Frequency (HSF, LSF) $\times$ Electrode locations (Fz, Cz, Pz) showed a significant main effect of electrode location ($F(1.62, 87.44) = 40.96$, $p < .001$, $\eta^2_G = 0.066$), a significant interaction between electrode location and culture, $F(1.62, 87.44) = 4.99$, $p = .014$, $\eta^2_G = 0.009$, as well as a significant interaction between electrode location and frequency, $F(1.48, 80.13) = 25.43$, $p < .001$, $\eta^2_G = 0.008$. These interactions reflect the convergence at Pz, relative to the other electrodes, of cultural groups and the relatively stronger response to low than high spatial frequencies.

3.2. Mass univariate analysis

The conventional approach that we used to select time window and electrode sites prior to electrophysiological analyses relies heavily on previous studies with similar paradigms (Luck, 2014). Because there are few previous studies that examined the impact of culture on the processing of spatial frequency, or even visual and attentional processes more broadly, this made it important to search more broadly for effects of culture on additional components in order to inform future work on the topic. In addition, testing all time points and channels might allow us to capture culture differences in the P3, which appeared to occur earlier in our paradigm, peaking slightly before the selected time window. Therefore, we further tested the effects of cultural background (Eastern, Western), spatial frequency (LSF, HSF), as well as stimulus lateralization (Left, Right) in a $2 \times 2 \times 2$ ANOVA. The ANOVAs were conducted at all electrodes and all time-points through mass univariate analysis, a data driven, cluster-based computational method that corrects for multiple comparisons. We included stimulus lateralization as an exploratory factor because some prior research indicates that hemispheres may differ in their sensitivity to different spatial frequencies, with the left hemisphere preferentially processing HSF information and the right hemisphere preferentially processing LSF information (Iidaka, Yamashita, Kashikura, & Yonekura, 2004; Kenemans, Baas, Mangun, Lijffijt, & Verbaten, 2000; Proverbio, Zani, & Avella, 1997; Zani & Proverbio, 1995).

3.2.1. Effects of spatial frequency

The mass univariate analysis revealed a significant main effect of spatial frequency at three spatial-temporal clusters (Fig. 3). The time-window of the first significant spatial-temporal cluster ($p = .006$), which ranged from 119 to 182 ms, was within the latency of the N1 component. It was located in anterior and central electrodes, and the maximum effect size within this cluster occurred at 158 ms, at electrode FC2. The time-window of the second cluster ($p < .001$), located across all

Table 1

Behavioral data comparing cultural groups on accuracy and reaction time for the oddball task.

	Detection rate ($M \pm SD$)	Reaction time ($M \pm SD$)
Easterners	99.5 $\pm$ 0.9%	426.3 $\pm$ 79.5 ms
Westerners	99.8 $\pm$ 0.2%	401.3 $\pm$ 63.0 ms

³ The main effect of spatial frequency persisted even when the prescription for corrective lenses (self-reported; coded as a 0 for those who did not wear corrective lenses) was entered as a covariate in the model. Although the potential for cultural differences was the primary concern, we included the covariate to assess whether it impacted the effect of spatial frequency.

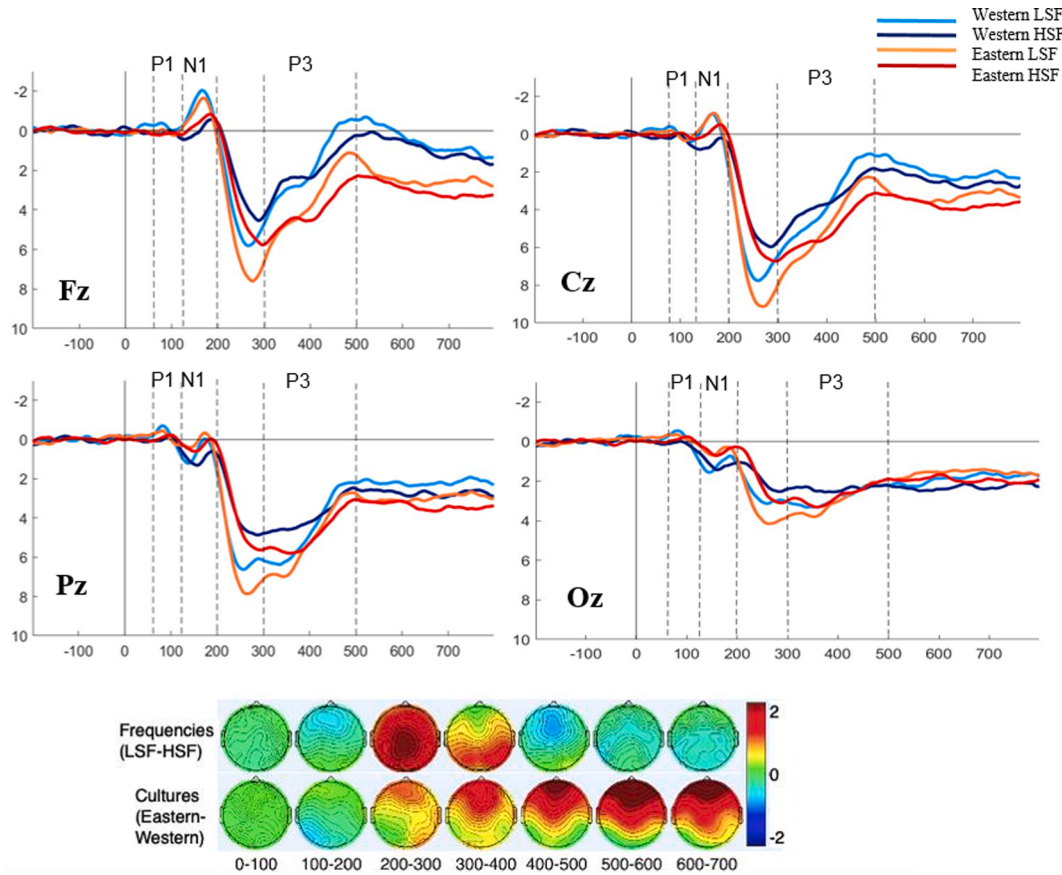


Fig. 2. Grand averaged ERPs from 4 electrodes (Cz, Fz, Pz, and Oz) showing the effects of spatial frequency and culture on the P1, N1, and P3. The topographic maps (bottom panel) depict the distribution of voltage differences from 0 ms to 700 ms post-stimulus onset. The color of the scalp maps reflected the difference between two frequency conditions (LSF minus HSF) for each cultural group, and the differences between two cultural groups (Eastern minus Western) for each time bin.

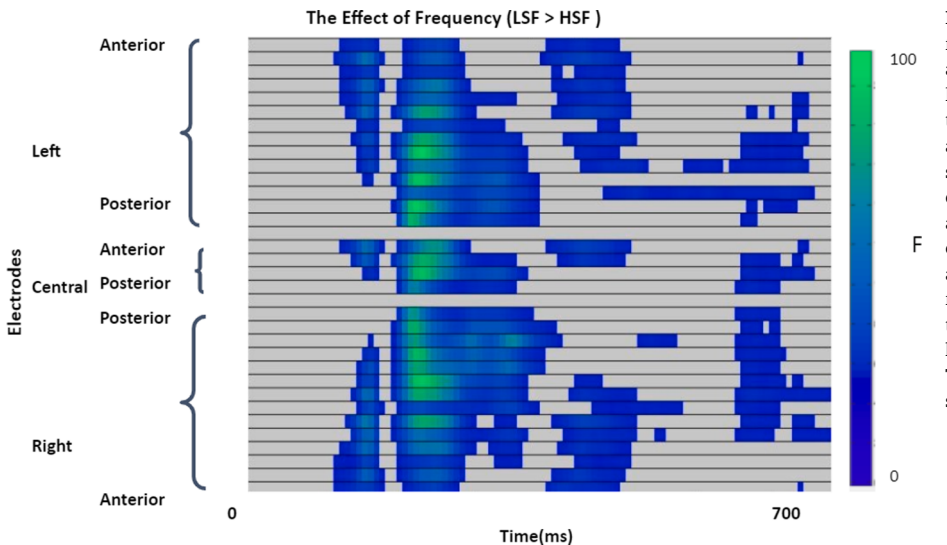


Fig. 3. The raster plot shows the effect of spatial frequency (LSF > HSF) from the mass univariate analysis of ERP data. The x-axis depicts time in milliseconds and the y-axis depicts electrode, with the top section corresponding to the left side of the scalp and the bottom section corresponding to the right side of the scalp, and central electrodes in the middle; left hemisphere electrodes are plotted from most anterior to most posterior and right hemisphere electrodes are plotted from most posterior to most anterior. Significant clusters for the effect of spatial frequency are depicted in color at the relevant timepoints and electrodes, with green reflecting a higher F-value than blue (see color bar to the right). Time point/electrode combinations not included in a significant cluster are in gray.

electrodes (see Fig. 3), ranged from 197 to 424 ms. This largely overlapped with the latency of the P3 component, which can reflect differences in attention to global (LSF) vs. local (HSF) information (Tian, Wang, Xia, Zhao, Xu, & He, 2018), as well as expectations (Noyce, & Sekuler, 2014). The effect reached its maximum size within this cluster at 229 ms, at electrode PO3. As can be seen in the figures, there was no evidence that these effects differed across hemispheres. The time-window of the third cluster ($p = .001$), located also across all

electrodes, ranged from 400 to 791 ms.

3.2.2. Effects of culture

This mass univariate analysis also revealed a significant main effect of culture at a spatial-temporal cluster ($p = .002$) located at frontal and anterior-frontal electrodes (Fig. 4). This effect's time-window spanned 275 to 791 ms. Within this cluster, the effect size was largest at 564 ms at electrode AF4. There were no statistically significant clusters for the

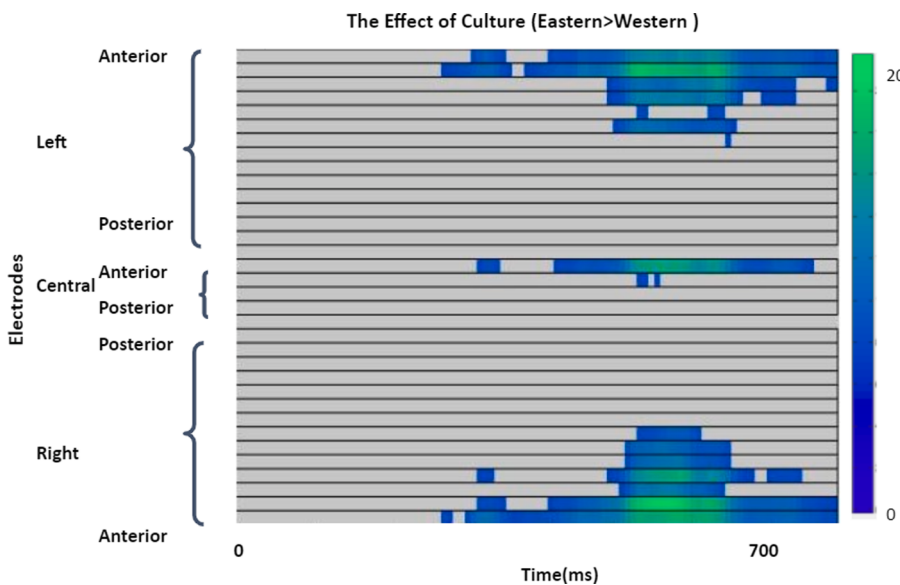


Fig. 4. The raster plot shows the effect of culture (Eastern > Western) from the mass univariate analysis of ERP data (top panel). The x-axis depicts time in milliseconds and the y-axis depicts electrode, with the top section corresponding to the left side of the scalp and the bottom section corresponding to the right side of the scalp, and central electrodes in the middle; left hemisphere electrodes are plotted from most anterior to most posterior and right hemisphere electrodes are plotted from most posterior to most anterior. Significant clusters for the effect of culture are depicted in color at the relevant timepoints and electrodes, with green reflecting a higher F-value than blue (see color bar to the right). Time point/electrode combinations not included in a significant cluster are in gray.

interaction between culture and spatial frequency, (all p s > 0.7).

Main effects of lateralization emerged in three clusters. The first ($p = .017$) and the second ($p = .002$) ranged from 143 to 299 ms and 291 to 541 ms at a broad range of electrodes. The third ($p = .008$) ranged from 572 to 791 ms at left posterior electrodes. However, there were no statistically significant clusters for the interactions between lateralization and any other factor (all p s > 0.07). The full mass univariate results are available in the Supplemental Materials.

4. Discussion

The results of this study reveal effects of spatial frequencies on ERPs, with larger responses to LSF than HSF, but show little evidence of cultural differences in the response to different spatial frequencies. Specifically, a frontal negativity around 150 ms was larger for the LSF Gabor than for the HSF one. The most striking finding was a posterior positivity that emerged across most of the channels around 300 ms. Although this effect emerged in the mass univariate analyses and not the region of interest analyses, it may reflect the P3 component. The region of interest analyses may have failed to capture this effect because the component peaked earlier than the selected time window. Prior research found that spatial frequency can modulate early sensory components such as the P1 and N1 (e.g., Martinez et al., 2001; Proverbio et al., 1998; Tian et al., 2018) as well as the P3 (Tian et al., 2018; Proverbio et al., 1998), in line with the anterior N1 and P3-like effects we report. The frontal activity could reflect this task's attentional demands (attending to the intermittent, oddball stimulus) and the Gabors' behavioral irrelevance (e.g., Zani & Proverbio, 1995). For the early components, however, our finding of predominantly anterior and central effects, rather than posterior effects over visual cortex is somewhat surprising. P1 and posterior N1 were predicted to emerge in occipital channels, but these effects did not emerge in either the region of interest or the mass univariate analyses. In addition, the lack of an interaction between frequency and lateralization in the mass univariate analysis is surprising, as previous work has shown that the left hemisphere preferentially processes HSF information and the right hemisphere preferentially processes LSF information (Iidaka et al., 2004; Kenemans et al., 2000; Proverbio et al., 1997; Zani & Proverbio, 1995). Perhaps the absence of lateralization effects reflects the fact that participants' only overt responses were to the oddball stimulus; that is, participants made no overt response to the Gabors. Moreover, effects of lateralization tend to emerge at posterior electrodes (e.g., Zani & Proverbio, 1995), which were not modulated by spatial frequency in this task. Across these studies, the stronger response

to lower than higher spatial frequency information is in line with the idea of "sensory precedence of global information" (Proverbio et al., 1998).

In terms of effects of culture, the ERP responses to high compared to low spatial frequencies generally did not differ across cultures. Contrary to our predictions that Westerners would show enhanced perceptual (P1, N1) responses to high spatial frequency information whereas Easterners would show enhanced responses to low spatial frequency information, there were no significant interactions between culture and spatial frequencies in the early components. The spatial frequency effects differed to some degree across cultures for the P3 at the Pz electrode, thought to reflect attentional processes, with a greater response to HSF for Easterners than Westerners. Although this could provide evidence of some attentional differences across cultures to different spatial frequencies, we are hesitant to over-interpret this finding. For one, the direction of the effect is not in line with prior behavioral research (Blais et al., 2008; McKone et al., 2010; Rodger et al., 2010; Tardif et al., 2017), in which LSF, not HSF, is relatively more salient for Easterners than Westerners. Furthermore, the finding may not be robust, as the patterns seems to depend on using each participant's peak amplitude rather than averaging across identical time points (as noted in the results section) and the effect was not seen in the mass univariate analyses. For these reasons, the finding of cultural differences in P3 at the Pz electrode needs to be replicated in future work.

Although our focus is on cultural effects that differ across frequencies, ERPs showed two overall cultural differences: a late, long-lasting frontal effect, peaking around 550 ms, and a posterior N1 component. Both these main effects of culture are difficult to interpret without ambiguity. The cultural effect in the N1 window presents a different interpretive challenge because the component does not have the expected topography (see discussion in the Results). The extended frontal effect in the mass univariate analyses also has an unusual time-course and topography. Although the effect reaches significance in the time window selected in the region of interest analyses for the P3, the prolonged time course and scalp distribution are not entirely consistent with a P3 effect as usually defined. In terms of interpreting the cultural differences, the long-lasting frontal effect is difficult to interpret because it could have come either from a negative-going component that is larger for Easterners or from a positive-going component that is larger for Westerners.

Assuming that the P3 component in our study did actually reflect cultural differences in attentional processes, that assumption could be further tested by manipulating the frequency and expectations for

stimuli composed of preferred vs. non-preferred spatial frequencies. More specifically, such a test would examine P3 when strong expectations were first built up and then violated by using different types of stimuli. Even more important, it is challenging to infer processing differences from main effects across groups. The differences in waveform morphologies may reflect overall differences between the groups in head shape (or how the cap fits the head) or in the positioning of neural generators relative to the scalp (Woodman, 2010). For example, East Asians' brains and skulls tend to be rounder than Caucasians' (Tang et al., 2018), which could alter how cortical signals are projected onto the scalp. Should the frontal effects represent a difference between Easterners and Westerners, principled inferences about process require that the boundary conditions be defined. For example, is the effect limited to the spatial frequency dimension? Is it produced in all or most visual tasks? Or does it extend more broadly, across a wide variety of perceptual and cognitive tasks? If a main effect of culture is seen without regard to task, it becomes more likely that it reflects cognitively uninteresting, anatomical differences across the groups.

The overall dearth of cultural differences in the response to high compared to low spatial frequency information simply could reflect a lack of power to detect effects: given our sample sizes, a relatively large between-groups difference would be needed for high power (for power of 0.8, Cohen's $d > 0.75$ in the size of the frequency effect would be needed). On the other hand, effects of frequency on the both the N1 and P3 were in the same direction and of approximately the same size for both groups and there is some evidence for modest cultural differences in the P3 at Pz based on the analyses targeting specific components. To further investigate potential effects of culture that we lacked the power to detect, we separately analyzed the effect of spatial frequency for each cultural group. See Supplemental Materials. The cultural groups do not show differences in the pattern of effects in the component analyses. In the mass univariate analyses, although both groups exhibit a significant main effect of frequency in the 200–300 ms range, there is some evidence of cultural differences in other time windows. Westerners exhibit a significant effect of frequency in an early cluster from 127 to 183 ms and Easterners exhibit a significant effect of frequency in a later cluster from 400 to 525 ms. Although these potential differences might be of interest to examine in future research, it is important to emphasize that cultural differences did not emerge in direct tests of the interaction and effects went in the same direction for each cultural group. Detecting an interaction due to differences in magnitude, rather than direction of effects, requires a high degree of power. For these reasons and the results across two sets of analyses (component-based and mass univariate), we think that there was no evidence of fundamentally different effects across cultures that simply failed to reach significance. Another consideration is whether ERPs can be used to detect any cultural difference that exists in the processing of spatial frequencies. Evaluating this possibility would require pairing a sensitive behavioral task with ERPs.

Aspects of our participant sample and/or the design of our task could have limited ability to detect cultural differences. Easterners in our sample had been in the U.S. on average for over two years but there was a range of time in the U.S. Cultural comparisons may be more robust when Eastern samples consist of immigrants new to the U.S., or even those who live in China and have not self-selected to move to the U.S. In terms of task design, cultural differences may emerge for particular spatial frequencies or perhaps more subtle distinctions between spatial frequencies are necessary to discern differences in the salience of certain spatial frequencies. The oddball detection task could have focused participants' attention in narrow space, which would have prevented cultural effects due to differences in the default breadth of attention (Boduroglu & Shah, 2017; Boduroglu, Shah, & Nisbett, 2009) from emerging on the task. Thus, the design of our task could have a similar impact as the spotlight technique used by Caldara, Zhou, & Miellet (2010), in which only a small portion of the stimulus is visible around the location being fixated. Their results indicated that when the

information available to participants was restricted, Easterners and Westerners used the remaining information similarly. However, when more information was available – the viewing window was not so restricted and viewers could see both eyes and the mouth while fixating on the nose – cultural differences were revealed. These differences were thought to reflect strategies in that cultural differences only emerged under conditions in which participants took in more information and had the ability to select and prioritize some aspects over others, but not when the incoming information was restricted, through small spotlights, to be identical across groups. Employing tasks that allow for participants to deploy attention over space more naturally could allow for more pronounced cultural differences. It is also possible that cultural differences are not present for such low-level tasks. There is some precedent for this possibility in the literature: Tardif et al. (2017) failed to find any differences in the contrast sensitivity functions of Easterners and Westerners. Thus far, cultural differences in the way that cultures use spatial frequencies for face perception (Miellet et al., 2013; Blais et al., 2008; Rodger et al., 2010; Tardif et al., 2017; Caldara et al., 2010; Kelly et al., 2010; Estephan et al., 2018) have not been found to extend to low-level stimuli, such as those used in the present study and also in Experiment 3 of Tardif et al. (2017).

In addition to allowing participants to deploy attention over space and utilizing designs that present more complex visual information to participants, perhaps filtered for different spatial frequencies, future work can employ tasks and decisions that build on the relatively passive task that was the focus of these analyses. Changing task contingencies, as seen in the prior research comparing the P3 across cultures in response to novel and target stimuli (Lewis et al., 2008; Wang et al., 2014), or pitting different spatial frequencies against each other in tasks requiring judgments may be useful in detecting cultural differences in expectations or what information is salient, as can be indexed by the P3 component.

Taken together, the considerations about aspects of our design and directions for future research suggest that task contingencies may be critical for understanding how culture impacts perceptual processing. This idea converges with Blais et al. (2021) who noted that “cultural differences in attentional deployment might interact with the nature of the task and stimuli” (p. 5). They went on to note that the range of available frequencies differs across tasks, with faces having a broader range than some other tasks; they called for additional studies of non-face objects whose frequency content was manipulated. We agree with their suggestions, and recommend that to detect cultural differences in the salience of various spatial frequencies future studies should (i) allow less constrained, more natural deployment of attention over space, (ii) set up competition amongst frequencies (Schyns & Oliva, 1999), and (iii) require overt information-based choices (as opposed to passive viewing). If with those modifications, a study still did not reveal cultural differences, that would suggest the importance of social stimuli, or even, as noted by Blais et al. (2021), that cultural differences occur in a face-specific mechanism. Before reaching that conclusion, it would also be necessary to assess cultural differences in the use of spatial frequencies in non-social scenes in order to examine potential relationships with cultural differences in object vs. context processing (e.g., Chua et al., 2005; Masuda & Nisbett, 2001).

Limitations of the study include some of our a priori choices for the region of interest analyses. We pre-registered analyses using peak amplitude, which can be challenging to interpret and more sensitive to noise and latency variations than mean amplitude (Luck, 2014). In some cases, such as for the P3, our selected time windows failed to capture the peak of effects. Mass univariate analyses complemented the region of interest analyses, providing more flexibility by testing for effects across all time windows and electrodes. The wider search space in which to detect effects, which is particularly useful given the small number of studies that use EEG to investigate cross-cultural cognition, occurs alongside potentially greater power to detect effects with this analysis approach (Fields & Kuperberg, 2020). In addition to measurement and

statistical issues, recruiting both samples from the United States could have minimized cultural differences. Specifically, East Asians who choose to study in the US might be more like Americans in terms of endorsement of cultural values (e.g., independence) than those who would be sampled from East Asian nations. However, much of the prior research on cultural differences (e.g., Lewis et al., 2008; Wang et al., 2014) samples and tests participants at one site and still finds effects of culture. Such an approach offers advantages when using cognitive neuroscience techniques, as hardware and procedures (e.g., potential differences in noise or capping procedures) will not vary across sites.

In conclusion, the results of this study support suggestions that when subjects are tested with low-level stimuli (Gabor patches) and without task demands, low spatial frequency, or global, information evokes larger responses in early attentional ERP components. However, ERP responses to high and low spatial frequencies did not differ across cultures, which is in line with other research that failed to find cultural differences with low-level stimuli (Tardif et al., 2017). Further work is needed, however, to assess whether this pattern holds across larger samples and a variety of different task demands. Finally, the present study highlights the advantages of mass univariate analyses for the study of cultural differences. As the underlying mechanisms that account for cultural differences across many cognitive processes are unclear and patterns of findings not always predicted by existing theories (Gutchess & Sekuler, 2019), an approach combining breadth and sensitivity offers many advantages to the nascent field of cultural neuroscience.

CRedit authorship contribution statement

Tong Lin: Data curation, Formal analysis, Investigation, Methodology, Project administration, Visualization, Writing – original draft, Writing – review & editing. **Xin Zhang:** Data curation, Investigation, Methodology, Project administration, Resources, Writing – original draft, Writing – review & editing. **Eric C. Fields:** Formal analysis, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Robert Sekuler:** Conceptualization, Funding acquisition, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Angela Gutchess:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.bandc.2021.105834>.

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