Vision Research 112 (2015) 45–54

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

A comparison of spatial frequency tuning for judgments of eye gaze and facial identity

Mark D. Vida [a,*], Daphne Maurer [b]

[a] Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, PA 15213, USA
[b] McMaster University, 1280 Main Street West, Hamilton, ON L8S 4L8, Canada

ARTICLE INFO

Article history:
Received 8 December 2014
Received in revised form 13 April 2015
Available online 14 May 2015

Keywords:
Face perception
Spatial frequency
Eye gaze
Facial identity
Noise masking
Ideal observer

ABSTRACT

Humans use the direction of eye gaze and facial identity to make important social judgments. We carried out the first measurements of spatial frequency (SF) tuning for judgments of eye gaze, and compared SF tuning for judgments of facial identity and eye gaze. In Experiment 1, participants discriminated between leftward and rightward shifts of gaze, or between two male faces or two female faces. Faces were masked with visual noise that blocked one of 10 SF bands. For each task and masking SF, we measured contrast thresholds for human observers, and used an ideal observer to measure the amount of visual information available to perform the task. As in previous research, low to mid SFs were most important for judgments of facial identity. Mid to high SFs were most important for judgments of eye gaze, and the highest SF important for these judgments was higher than that for identity. In Experiment 2, participants discriminated horizontal and vertical shifts of gaze. The highest SF important for judgments of gaze did not differ between the horizontal and vertical axes. However, SFs above and below this value were more important for judgments of vertical shifts of gaze than for horizontal shifts of gaze. These results suggest that the visual system relies on higher SFs for judgments of eye gaze than for judgments of facial identity, and that SF tuning is broader for judgments of vertical shifts of gaze than for horizontal shifts of gaze.

1. Introduction

Humans use facial identity to categorize (e.g., familiar versus unfamiliar) and individuate (e.g., Bob versus Jim) people, and use the direction of people's gaze to make inferences about their mental and emotional states (Argyle & Cook, 1976; Emery, 2000). Adult humans rely primarily on low (coarse details) to mid (finer details) spatial frequencies (SFs) when discriminating facial identity (e.g., Gao & Maurer, 2011; Goffaux & Rossion, 2006). Previous studies have not examined SF tuning for judgments of eye gaze. Here, we carried out the first investigation of SF tuning for judgments of eye gaze, and compared that tuning to the tuning for judgments of facial identity.

1.1. Spatial frequency tuning for judgments of facial identity

Previous studies have examined the role of SF in humans' ability to discriminate between facial identities. One method used to investigate this question involves blocking access to a target SF band by adding visual noise (Gao & Maurer, 2011; Näsänen, 1999; Ojanpää & Näsänen, 2003) or another pattern (e.g., a sinusoidal grating) (Tieger & Ganz, 1979) in the target band, an approach known as masking. The more important the target band is for performance on the task, the more masking is expected to disrupt performance. Spatial frequency tuning for at least some non-changeable (e.g., facial identity) and changeable (e.g., facial expression) facial signals varies only slightly with viewing distance (e.g., Gao & Maurer, 2011). Hence, throughout this article, we report measures of SF tuning for judgments of both types of facial signals in units of cycles per face width (c/fw), rather than in cycles per degree. We use "mid SFs" to refer to the range (around 8–17 c/fw) of SFs most consistently implicated in face perception (Gao & Maurer, 2011; Näsänen, 1999). We use "low SFs" and "high SFs" to refer to SFs above and below this range, respectively. Masking mid SFs leads to the greatest disruption in discrimination of facial identity (Gao & Maurer, 2011; Näsänen, 1999; Ojanpää & Näsänen, 2003; Tieger & Ganz, 1979), a result suggesting that SFs in this range are particularly important for judgments of facial identity.

Previous studies have also investigated SF tuning for judgments of facial identity by applying a SF filter directly to a face image (Costen, Parker, & Craw, 1996; Fiorentini, Maffei, & Sandini,

* Corresponding author.
E-mail addresses: markvida@andrew.cmu.edu (M.D. Vida), maurer@mcmaster.ca (D. Maurer).

http://dx.doi.org/10.1016/j.visres.2015.04.018
0042-6989/

1983; Hayes, Morrone, & Burr, 1986; Näsänen, 1999). In this approach, performance is expected to be best when information important for performance on the task is not removed by the filter. Studies using this approach have reported that discrimination of facial identity is best when SFs between 8 and 16 c/fw are included in the face image (Costen, Parker, & Craw, 1996; Näsänen, 1999), with some studies reporting a range including lower (5 c/fw) (Fiorentini, Maffei, & Sandini, 1983) or higher (20 c/fw) (Hayes, Morrone, & Burr, 1986) values. Hence, as with the masking approach (Gao & Maurer, 2011; Näsänen, 1999; Ojanpää & Näsänen, 2003; Tieger & Ganz, 1979), evidence from studies using the filtering approach indicates that mid SFs are particularly important for judgments of facial identity.

Human observers' ability to discriminate facial identity may depend critically on the amount of information available to perform the task. The amount of low-level visual information available to discriminate facial identity increases with SF (Gao & Maurer, 2011; Gold, Bennett, & Sekuler, 1999). After adjusting estimates of human sensitivity to take into account the amount of information available to perform the task in each SF band, humans appear to rely approximately equally on low to mid SFs, with a steep drop-off in importance for higher SFs (Gao & Maurer, 2011). Although there is more information available to discriminate facial identity at higher SFs, humans appear not to make efficient use of it, except when performing a task in which faces differ only in the shape of facial features (Goffaux et al., 2005).

1.2. Sensitivity to the direction of eye gaze

Adult humans are highly sensitive to shifts of eye gaze: they can detect horizontal (e.g., Symons et al., 2004; Vida & Maurer, 2012b) and vertical/oblique (Bock, Dicke, & Thier, 2008) shifts of 1–2° in gaze relative to objects in the environment. This high sensitivity allows precise judgments of the focus of others' visual attention (Argyle & Cook, 1976).

Previous studies have not examined SF tuning for judgments of eye gaze. However, existing data and models allow tentative predictions about the role of SF in gaze perception. One relevant line of research has investigated the extent to which changeable (e.g., facial expression, eye gaze) and non-changeable (e.g., facial identity) facial signals are processed by separate mechanisms. Given that these two types of facial signals can carry independent social information about people, allocating each signal to a separate pathway could allow enhanced processing of each signal. However, it is also important to integrate information across changeable and non-changeable facial signals in at least some situations (e.g., when monitoring the emotional state of a specific individual). Integration between pathways for processing these two types of signals may support social perception in these situations (Baseler et al., 2014).

Evidence that the visual system has separate mechanisms for processing changeable and non-changeable facial signals comes from findings that anatomically distinct regions of human cortex are sensitive to these two types of signals (Hoffman & Haxby, 2000). The extent of functional overlap in processing of these two types of facial signals is not well-established. Behavioral studies indicate that variation in changeable facial signals can affect the speed of judgments of non-changeable facial signals, and vice versa. However, these effects can be abolished by manipulating the discriminability of the stimuli (Ganel, 2011; Wang et al., 2013). There is also evidence that variation in facial identity affects responses to changeable facial signals in posterior superior temporal sulcus, a cortical region consistently implicated in processing of changeable facial signals (Baseler et al., 2014). This interaction could reflect the integration of information from changeable and non-changeable facial signals.

Functionally separate components of the pathways for processing changeable and non-changeable facial signals could differ in SF tuning. Consistent with this hypothesis, a masking study found that judgments of facial expression are tuned to higher SFs than judgments of identity (Gao & Maurer, 2011). Functionally overlapping components of these two pathways may have similar SF tuning. Hence, comparing SF tuning between different types of changeable and non-changeable facial signals may provide information about the extent to which the visual system uses a common set of resources to process these different types of signals.

Subcortical neural mechanisms could also influence SF tuning for judgments of eye gaze. In one model, humans possess a subcortical neural mechanism that is sensitive to face identity and the direction of gaze, and responds selectively to low SFs (Johnson, 2005; Senju & Johnson, 2009). Such a mechanism could account for findings that newborns, who lack sensitivity to high SFs (Banks & Salapatek, 1978; Norcia & Tyler, 1985; Norcia, Tyler, & Hamer, 1990), nevertheless look longer at faces with direct gaze than at those with gaze averted far to one side (Farroni et al., 2002). The continued functioning of this mechanism in adults could lead to greater reliance on low SFs when discriminating the direction of eye gaze and facial identity. Furthermore, differences in reliance on low SFs for eye gaze and facial identity could reflect differences in the involvement of this subcortical mechanism.

In summary, previous research suggests that mechanisms underlying adults' judgments of facial identity are tuned to low to mid SFs (e.g., Gao & Maurer, 2011). Previous research also suggests at least partially separate mechanism to process these two facial signals (Baseler et al., 2014; Hoffman & Haxby, 2000). Previous studies have not measured SF tuning for judgments of eye gaze, and have not compared this tuning for judgments of facial identity and gaze. The purpose of the current study was to investigate these questions. In Experiment 1, participants viewed faces masked with noise filtered to contain a narrow range of SFs, with the centre SF of the noise varying between blocks. The task was to discriminate between leftward and rightward gaze, or to discriminate between two facial identities. We used an adaptive staircase procedure to measure participants' contrast thresholds, and used an ideal observer analysis to take into account the amount of information available to perform the task. In Experiment 2, we used a method similar to that of Experiment 1 to compare SF tuning for judgments of horizontal and vertical shifts of gaze.

2. General method

2.1. Apparatus

For Experiment 1, stimuli were displayed on a Dell P1130 21 inch CRT display set to a resolution of 1152×870 and a refresh rate of 75 Hz. The display had 256 grayscale levels. The mean luminance of each stimulus and the background against which all stimuli were presented were set to the mean luminance of the display. The experiment was run in MATLAB R2008a (MathWorks) using the Psychophysics Toolbox extensions (Brainard, 1997) on an Apple Mac Pro computer. Participants used a chinrest to maintain a constant head position.

2.2. Face images

All face images came from a stimulus set used in previous studies of gaze perception (Vida & Maurer, 2012a, 2013). We used images of two adult females and two adult males photographed fixating targets 4.8° and 8° to the left/right and above/below the camera lens. Previous studies using these stimuli indicate that 4.8° and 8° deviations are beyond the range of directions of gaze that consistently lead to the perception of direct gaze (Vida & Maurer, 2012a, 2013). We converted each face image to grayscale format, and applied an oval Gaussian window to each face to remove hair cues (see Fig. 1). Face images were 10.5° wide at the testing distance of 60 cm. Hence, an SF of 20 c/fw corresponded to an SF of approximately 2 c/degree of visual angle. Stimuli in Experiment 1 were images of the four models displaying horizontal shifts of gaze. Stimuli in Experiment 2 were images of the same models displaying horizontal and vertical shifts of gaze. To ensure that differences in the amplitude spectrum would not lead to differences in our measurements of SF tuning, we set the amplitude spectrum of each face image to the average of all images presented within the same experiment.

2.3. Spatial frequency manipulation

On each trial, the experimental software generated a Gaussian white noise mask with the same dimensions as the face image, and added the mask to the face image. The noise mask was filtered in the frequency domain by a bandpass Gaussian filter (see Supplementary Fig. 1 for filter functions) with a bandwidth of 1.58 octaves (full width at half height), and a center SF of 2.8, 4, 5.7, 8.0, 11.3, 16, 23, 32, 45, or 64 c/fw. All other procedures used to generate the noise mask are described in Gao and Maurer (2011). The spectral density of the noise (N) is defined as:

$$N = \frac{c_{\mathrm{RMS}}^2}{\pi(f_2^2 - f_1^2)} \tag{1}$$

where c_{RMS}^2 is the RMS contrast of the noise, and f_1^2 and f_2^2 are the lower and higher cut-off frequencies of the noise band, respectively (Näsänen, 1999). RMS contrast was held constant across masking frequencies, whereas the difference between the upper and lower bounds of the filter functions increased with masking frequency (see Supplementary Fig. 1). Hence, N decreased with masking frequency, as it did in previous studies using similar methods (Gao & Maurer, 2011; Näsänen, 1999). Assuming that contrast thresholds are proportional to N (Näsänen, 1999), the decrease in N with increasing masking frequency would be expected to decrease contrast thresholds at higher masking frequencies, relative to a situation in which N increased or remained constant with increasing masking frequency. Our primary aim in the current study was to compare SF tuning for judgments of different types of facial signals. Since the parameters of the noise were the same for all types of facial signals presented in the current study, variation in spectral density across masking frequencies cannot account for any differences in SF tuning between different types of signals.

2.4. Ideal observer analysis

We used an ideal observer based on that of Gao and Maurer (2011) to measure the amount of information available to perform each task. An ideal observer is a simulation that uses a theoretically optimal strategy to perform a perceptual task (Tjan et al., 1995). The performance of the ideal observer is limited only by the amount of visual information available to perform the task (Tjan et al., 1995). Therefore, better performance by the ideal observer indicates that there is more information available to perform the task. On each trial, the ideal observer calculated the probability that the stimulus was from each of two categories (e.g., leftward or rightward gaze), and decided that the stimulus was from the category with the highest probability (see Gao & Maurer, 2011, for full description).

We calculated the efficiency of human performance from the ratio between the contrast energy associated with the contrast threshold for the ideal observer (E_{ideal}) and the contrast energy associated with the contrast threshold for human observers (E_{human}) (Gao & Maurer, 2011):

$$\text{Efficiency} = \frac{E_{\mathrm{ideal}}}{E_{\mathrm{human}}} \tag{2}$$

Contrast energy is defined as:

$$E = c_{\mathrm{RMS}}^2 na \tag{3}$$

where n is the number of pixels in the image and a is the area of a single pixel (Gao & Maurer, 2011; Näsänen, 1999). As in a previous study using a similar method (Gao & Maurer, 2011), we converted efficiency to relative sensitivity by taking the logarithm of the reciprocal of efficiency.

2.5. Staircase procedure

For both human and ideal observers, we used a staircase procedure to adjust the RMS contrast of the face images according to observers' responses, and to estimate the contrast threshold. On the first trial of each run, the RMS contrast of the face image was 0.2. The contrast of the face image decreased after three consecutive correct responses, and increased after a single incorrect response. The procedure ended after 10 reversals. We calculated the contrast threshold from the geometric mean of the RMS contrast values of the last six reversals, a value corresponding to 79%

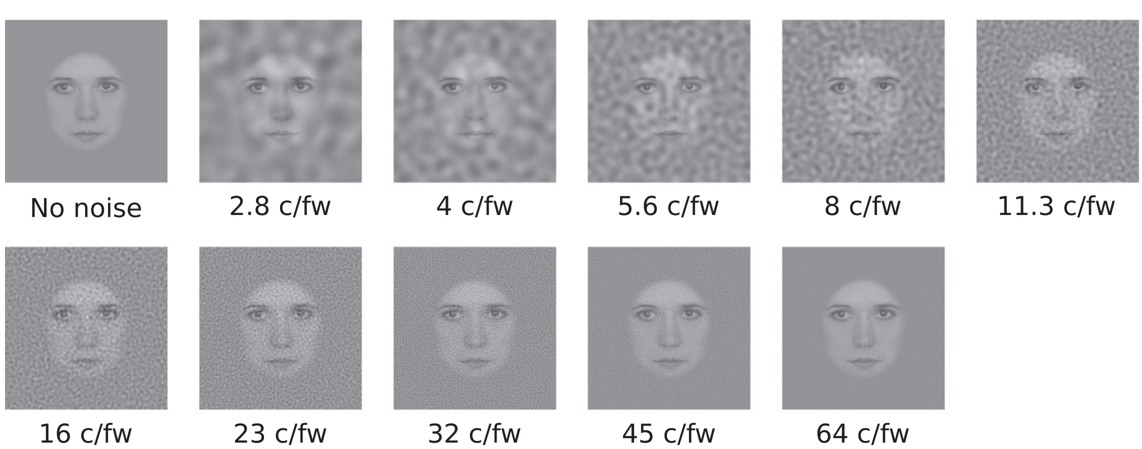

Fig. 1. Examples of stimuli presented in the current study. In each example, the face image shows the same female model fixating a target 8° to the left.

accuracy (Prins & Kingdom, 2009). All other details concerning the staircase procedure are described in Gao and Maurer (2011).

3. Experiment 1

In Experiment 1, we examined SF tuning for judgments of facial identity and eye gaze. In the identity task, participants learned two facial identities (both male or both female), then discriminated between them with masking noise superimposed. In the eye gaze task, participants viewed faces, again with masking noise superimposed, and judged whether the model was looking to the left or right. The masking noise was centred on 10 different narrow SF bands, except for one condition with no noise. To adjust our measurements of human sensitivity to take into account the amount of information available to perform the task, we compared human performance to that of an ideal observer (see Section 2.4 and Gao & Maurer, 2011, for full description of ideal observer).

3.1. Participants

Participants were four adults (NF, KG, HL, MC, age range: 20–21 years) from McMaster University. All participants had previous experience with psychophysical experiments, were naïve to the purpose of the experiment, and had normal or corrected-to-normal vision. Each participant completed testing over a period of 2 weeks.

3.2. Design

Each participant completed the identity discrimination task and the gaze discrimination task. Half of the participants completed the identity task first and the gaze task second, with the other half receiving the opposite order.

3.2.1. Facial identity task

Participants discriminated between the two male models in one condition, and discriminated between the two female models in a separate condition. Each participant completed these conditions in a random order. For each model, there were four images showing the model with four different directions of gaze (4.8° left/right and 8° left/right). Each participant completed two runs for each of the 11 noise masking conditions (no noise and 10 centre SFs). For each run, participants completed the no noise condition first, and completed all other noise conditions in a random order. For each participant and noise condition, we calculated the RMS contrast threshold from the mean of the two runs. In total, there were 44 thresholds (two model sexes [male, female], 11 noise conditions, two runs) for each participant.

3.2.2. Eye gaze task

Participants discriminated between leftward and rightward gaze. Gaze was shifted 4.8° to the left/right in one condition, and was shifted 8° to the left/right in a separate condition. Each participant completed these conditions in a random order. For each gaze condition, there were images from four models (two male, two female). In total, there were 44 thresholds (two gaze conditions [4.8°, 8°], 11 noise conditions, two runs) for each participant. All other details were the same as in the facial identity task.

3.3. Procedure

The protocol was approved by the McMaster Research Ethics Board. We obtained written consent from each participant. The work was carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

3.3.1. Facial identity task

The identity task began with three training phases, which were included to ensure that participants were able to discriminate between the face identities that would be presented throughout the task. In phase one, participants viewed each face identity with four directions of gaze (4.8° left/right and 8° left/right) twice. Each image was presented for 2 s. A text label identifying the face as face 1 or face 2 was presented under the face image. In phase two, participants viewed each face for 500 ms. Participants judged the identity of each face by pressing one of two keys on a computer keyboard. Participants received auditory feedback indicating whether their responses were correct or not (a 1000 Hz tone for correct responses and a 400 Hz tone for incorrect responses). Phase three was the same as phase two, with the exception that no feedback was presented. Participants were required to respond correctly to all faces in phases 2 and 3. Training was terminated after participants met this requirement.

After completing training, participants began the testing session. Faces were presented as in the second and third training phases. Participants entered responses as in the second and third training phases, and received auditory feedback as in the second training phase.

3.3.2. Eye gaze task

The eye gaze task began with training to ensure that participants were able to discriminate the shifts of gaze that would be presented throughout the task. In the first training phase, each of the four models was shown displaying each of the four directions of gaze (4.8° left/right and 8° left/right). Display settings were the same as in the facial identity task. Participants indicated whether the face was looking to the left or right by pressing one of two keys on a computer keyboard. Participants received auditory feedback as in the identity task. The second training phase was identical to the first phase except that participants received no auditory feedback. Requirements for completing training were the same as in the identity task. After completing training, participants began the testing session. The task and display settings were the same as in the training phases, and participants received auditory feedback as in the second training phase.

4. Results and discussion

4.1. Contrast thresholds

In the current noise masking paradigm, a higher contrast threshold for a given masked SF band indicates that the band was more important for human performance, but without taking into account the amount of information available to perform the task. For the identity task, contrast thresholds were highest at around 11–16 c/fw. In contrast, thresholds for eye gaze appear to be highest at around 23 c/fw (see Figs. 2 and 3A).

To measure the characteristics of the masking functions, we fit a Gaussian function to each participant's data. The Gaussian function is defined as:

$$Y = A \times \exp\left(\frac{-(x-\mu)^2}{2\sigma^2}\right) \tag{4}$$

where x is SF in log units, Y is the participant's contrast threshold, A is the peak contrast threshold, μ is the SF corresponding to the peak, and σ represents the bandwidth of the masking function. For each task and condition, we calculated the mean position of the peak across participants, and calculated the bootstrapped 95% confidence interval (CI) using 2000 bootstrapped samples. For the identity task, the peak was at 14.31 c/fw (95% CI = 13.23–14.99) for female faces and 15.68 c/fw (95% CI = 13.99–17.48) for male faces. These peak

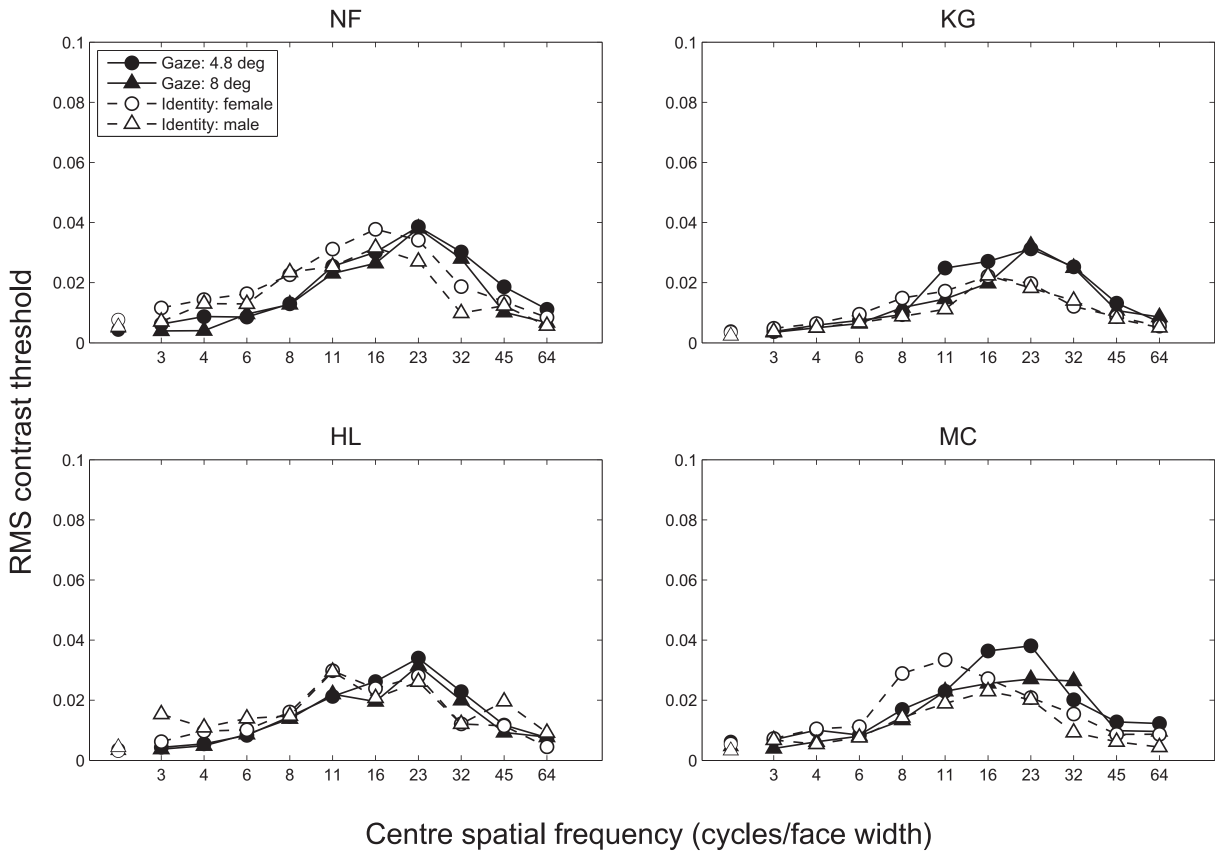

Fig. 2. Results for individual human observers in Experiment 1. Each plot shows the RMS contrast threshold (mean of two runs) for a single participant, as a function of task, condition, and the centre spatial frequency of the bandpass filter applied to the noise mask. Unlabeled data points to the far left of the x axis show the data for blocks in which no visual noise was added to the face image.

values are within the range (approximately 8–16 c/fw) reported in previous studies of SF tuning for judgments of facial identity (Costen, Parker, & Craw, 1996; Gao & Maurer, 2011; Hayes, Morrone, & Burr, 1986; Näsänen, 1999; Ojanpää & Näsänen, 2003; Tieger & Ganz, 1979). For the eye gaze task, the peak was at 19.39 c/fw (95% CI = 18.52–20.31) for 4.8° deviations of gaze, and 19.67 c/fw (95% CI = 18.80–21.18) for 8° deviations of gaze. The lack of overlap between the 95% confidence intervals for the eye gaze and identity tasks indicates that noise masking lead to the greatest disruption in performance at a higher SF for judgments of eye gaze than for judgments of identity.

4.2. Ideal observer

For each task and condition, we used an ideal observer to estimate the amount of information available to perform the task. As shown in Fig. 3B, the ideal observer performed similarly for the identity and gaze tasks. Unlike human observers, whose contrast threshold functions peak at mid SFs, the contrast thresholds for the ideal observer increase with increasing SF. Hence, for both tasks, the amount of information available to perform the task increased with SF. The same pattern has been reported for facial identity in previous studies (Gao & Maurer, 2011; Gold, Bennett, & Sekuler, 1999). To evaluate the similarity of the shapes of the tuning curves for each task and condition, we first found the best fitting function to the mean tuning curve across all tasks and conditions. A quadratic function $f(x) = p_1x^2 + p_2x + p_3$ (p_1 = 1.64e-05, p_2 = −4.15e-05, p_3 = 4.30e-05) provided a good fit (r^2 = 0.99). We then fit a quadratic function to the curve for each task and condition using the same p_1 and p_2 values as in the previous step, but allowing p_3 to vary since p_3 affects the height but not the shape of the curves. A one-way ANOVA on the squared residuals of the fits to the four curves revealed no significant difference, $p > .4$, a result suggesting that the tuning curves for the ideal observer had a similar shape for the facial identity and eye gaze tasks.

4.3. Relative sensitivity

Using Eq. (2), we calculated efficiency, an estimate of human sensitivity that takes into account the amount of information available to perform the task (see Fig. 3D). Masking at some SFs leads to large drops in efficiency. These SFs are considered to be most important for human performance, because the addition of noise at these SFs causes the greatest disruption in human performance relative to the performance of the ideal observer. To present human sensitivity in a more intuitive format (higher value reflects greater importance for human performance), we converted efficiency to relative sensitivity by calculating the logarithm of the reciprocal of efficiency (see Gao & Maurer, 2011).

For the facial identity task, relative sensitivity was high from low (2.8 c/fw) to mid (around 11–16 c/fw) SFs, and dropped off sharply for higher SFs (see Fig. 3D). Unlike human contrast thresholds for identity, there was no obvious peak in the curves for the ideal observer, similar to a previous study using a similar method (Gao & Maurer, 2011). For the eye gaze task, relative sensitivity increased from low to mid SFs, and dropped off sharply above 23 c/fw. This pattern clearly differs from that observed for identity in our study and in previous work (Gao & Maurer, 2011).

To quantify the differences in relative sensitivity between the identity and eye gaze tasks, we fit a piecewise linear regression

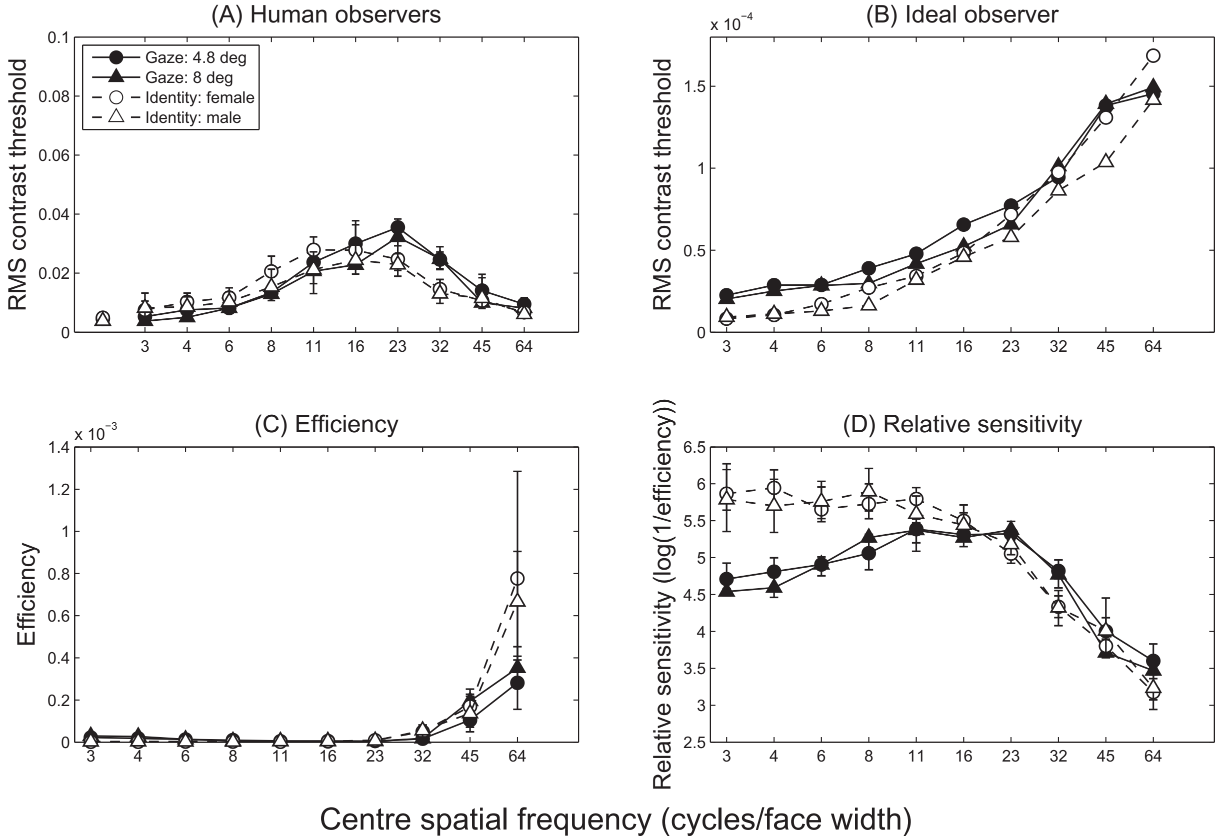

Fig. 3. Group results for human observers and results for ideal observer in Experiment 1, as a function of task, condition, and the centre spatial frequency of the bandpass filter applied to the noise mask. Error bars show the bootstrapped 95% confidence interval. (A) Mean RMS contrast threshold for human observers. All other details as in Fig. 2. (B) Mean RMS contrast threshold for the ideal observer. Error bars were so small that they were occluded by the data points. (C) Mean efficiency for human observers, as a function of task. (D) Mean relative sensitivity for human observers, as a function of task.

model (Muggeo, 2003) to the relative sensitivity curve for each participant and task. The best-fitting model allows estimates of the optimal number of adjacent linear functions needed to fit the data, and estimates the optimal location of the breakpoints between these functions. For each participant and task, the relative sensitivity curve was best fit by two adjacent linear functions, with a single breakpoint. The location of the breakpoint provides an estimate of the highest SF important for human performance on the task. The slopes of the linear functions above and below the breakpoint reflect the importance of SFs above and below the breakpoint (e.g., a positive slope indicates that importance increases with increasing SF). We used a bootstrapping procedure with 1000 iterations to estimate the 95% confidence interval for the breakpoint, and for the upper and lower slopes.

The mean breakpoint was 15.91 c/fw (95% CI = 11.67–17.80) for the identity task, and 20.65 c/fw (95% CI = 19.10–21.92) for the eye gaze task. Since the confidence intervals for the two tasks did not overlap, we conclude that the breakpoint was at a higher SF for the eye gaze task. This difference indicates that the highest SF important for judgments of eye gaze was higher than that for judgments of identity, even when taking into account the amount of information available to do the task, as identified by the ideal observer analysis.

The mean lower slope was −0.31 (95% CI = −.54 to .04) for the identity task, and 1.06 (95% CI =.99–1.11) for the eye gaze task. Since the confidence intervals for the two tasks did not overlap, we conclude that the lower slopes differed between the tasks. Since the confidence interval overlapped zero for the identity task, but not for the eye gaze task, we conclude that the slope differed from zero for the eye gaze task, but not for the identity task. The positive lower slope for the eye gaze task indicates that as SF increased up to the breakpoint, observers made increasing use of the information available. In contrast, the flat lower slope for the identity task indicates that information at SFs below the breakpoint was approximately equally important.

The mean upper slope was −4.12 (95% CI = −4.44 to −3.72) for the identity task, and −4.28 (95% CI = −4.52 to −3.90) for the eye gaze task. The negative and overlapping slopes for the two tasks suggests that as SF information increased above the breakpoint, observers made less use of it, despite information in the higher SFs becoming more informative according to the ideal observer analysis.

Together, these results suggest that whereas low to mid SFs are most important for judgments of facial identity, a range of mid SFs extending to higher SFs is most important for judgments of horizontal shifts of gaze.

5. Experiment 2

In Experiment 2, we used the method described for judgments of eye gaze in Experiment 1 to compare SF tuning for judgments of horizontal and vertical shifts of gaze.

5.1. Participants

Participants were six adults (NF, KG, HL, MC, MR, AP, age range: 20–21 years) from McMaster University. All participants except

MR and AP also participated in Experiment 1. MR had previous experience with psychophysical experiments, but AP did not. All other details were the same as in Experiment 1.

5.2. Design and Procedure

Each participant completed a horizontal gaze task and a vertical gaze task using the same four models as in Experiment 1. In the horizontal version, participants viewed faces in which gaze was shifted to the left or right, and judged whether gaze was shifted to the left or right. In separate blocks, gaze was shifted 4.8° or 8° to either side. In the vertical version, participants viewed faces in which gaze was shifted upward or downward and judged whether gaze was directed upward or downward. In separate blocks, gaze was shifted 4.8° or 8° upward or downward. Half of the participants completed the horizontal version first and the vertical version second, with the other half receiving the opposite order. All other details were the same as in the eye gaze task in Experiment 1.

6. Results and discussion

6.1. Contrast thresholds

As shown in Figs. 4 and 5A, contrast thresholds tended to be highest around 16–32 c/fw for judgments of both horizontal and vertical shifts of gaze. We fit a Gaussian function to each participant's data for each task and condition, as in Experiment 1. For the horizontal gaze task, the mean position of the peak was at 19.18 c/fw (95% CI = 17.64–20.94) for 4.8° deviations of gaze, and at 18.39 c/fw (95% CI = 17.68–20.32). For the vertical gaze task, the peak was at 21.41 c/fw (95% CI = 18.40–25.25) for 4.8° deviations of gaze, and at 19.50 c/fw (95% CI = 18.25–21.40) for 8° deviations of gaze. The overlap in the confidence intervals for each task and condition indicates that the peak contrast threshold was at a similar SF for horizontal and vertical shifts of gaze.

6.2. Ideal observer

As shown in Fig. 5B, the ideal observer performed similarly for horizontal and vertical shifts of gaze. We used the method described in Experiment 1 to test whether the shapes of the tuning curves differed between tasks and conditions. A quadratic function $f(x) = p_1x^2 + p_2x + p_3$ (p_1 = 1.53e-05, p_2 = −3.75e-05, p_3 = 4.53e-05) provided a good fit (r^2 = 0.99) to the mean across tasks. As in Experiment 1, we fit a quadratic function to the mean of each task using the same p_1 and p_2 values as estimated in the previous step, but allowing p_3 to vary. A one-way ANOVA on the squared residuals of the fits to the four curves revealed no significant difference, $p > .9$, a result indicating that there was no significant difference in the shapes of the curves. For each task and condition, contrast thresholds increased with increasing SF (see Fig. 5B), a pattern indicating that the amount of low-level visual information available to perform each task increased with SF, and did so in a similar manner for each task.

6.3. Relative sensitivity

For each task, we calculated efficiency and relative sensitivity as in Experiment 1 (see Fig. 5D). For judgments of horizontal shifts of gaze, relative sensitivity increased from low (2.8 c/fw) to mid (around 16–20 c/fw) SFs, and dropped off above around 20 c/fw, as it had in Experiment 1. For judgments of vertical shifts of gaze, relative sensitivity remained high from low (2.8 c/fw) to mid

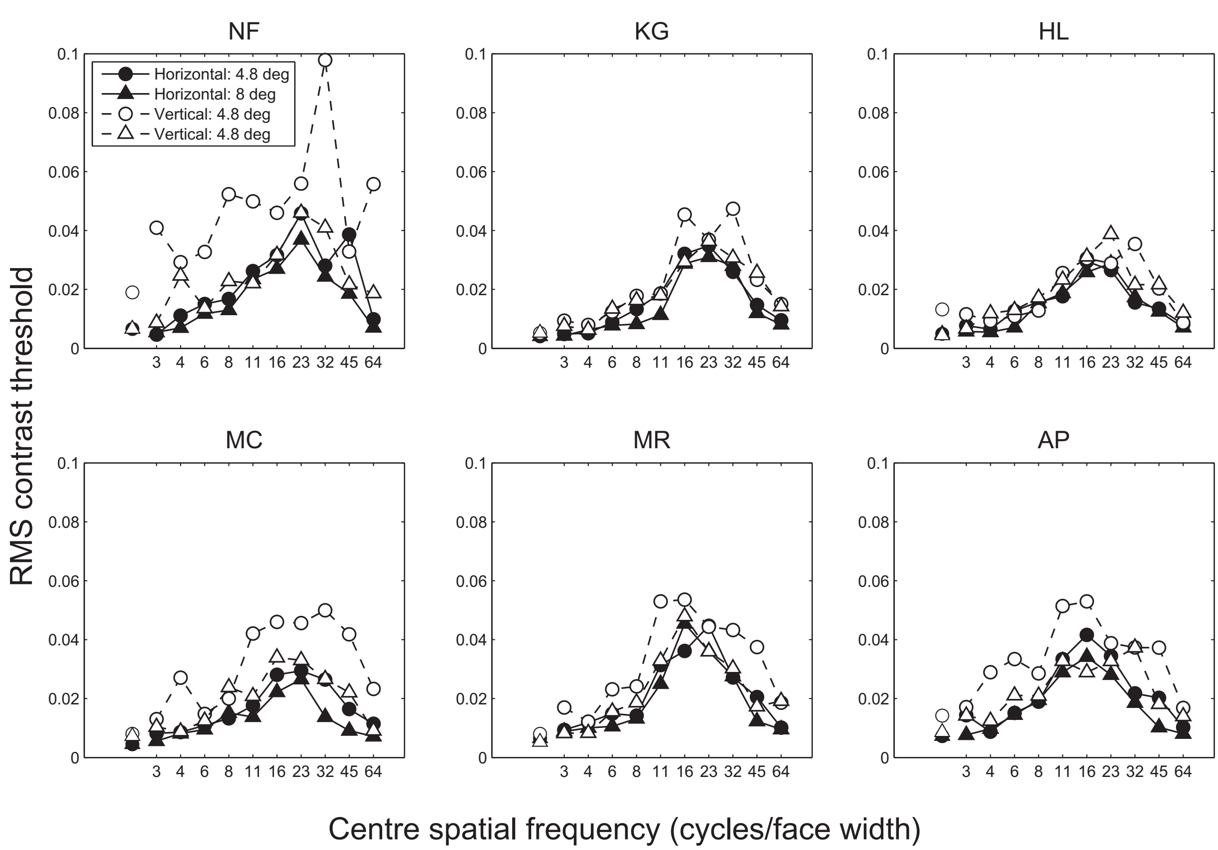

Fig. 4. Results for individual human observers in Experiment 2. All other details as in Fig. 2.

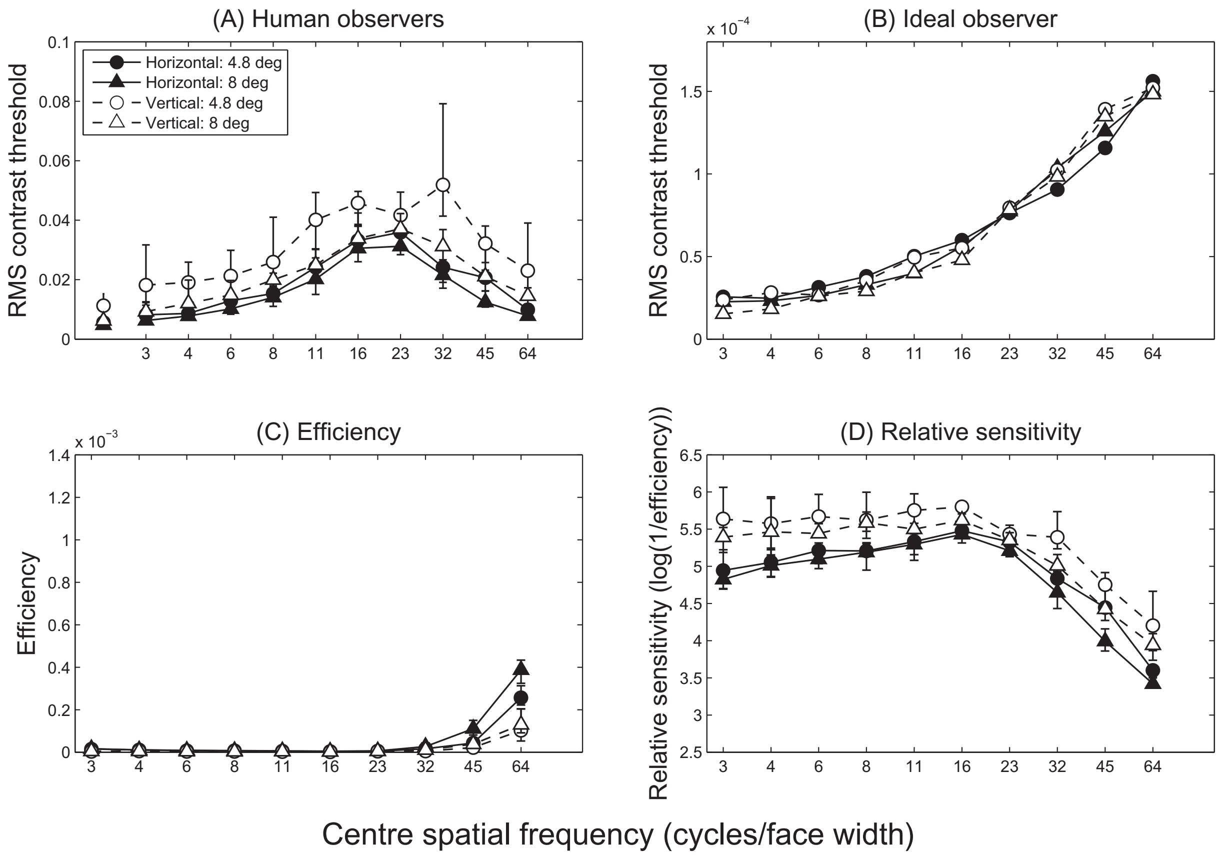

Fig. 5. Group results for human observers and results for ideal observer in Experiment 2. All other details as in Fig. 3.

(around 20 c/fw) SFs, and dropped off above around 20 c/fw. As in Experiment 1, we fit a piecewise linear regression model (Muggeo, 2003) to the relative sensitivity function for each participant and task (horizontal, vertical), and calculated the location of the breakpoint, the lower slope and the upper slope. The breakpoint was at 21.65 c/fw (95% CI = 19.43–25.20) for horizontal shifts of gaze, and at 21.58 c/fw (95% CI = 19.13–24.48) for vertical shifts. The overlap in the confidence intervals indicates that the highest SF important for judgments of gaze is similar for horizontal and vertical shifts of gaze.

The lower slope was .64 (95% CI = .54–.79) for judgments of horizontal shifts of gaze, and .20 (95% CI = −.09 to .50) for judgments of vertical shifts. The lack of overlap in the confidence intervals indicates that the lower slope was steeper for judgments of horizontal shifts. The upper slope was −4.45 (95% CI = −5.97 to −3.89) for judgments of horizontal shifts, and −3.42 (95% CI = −3.86 to −3.09) for judgments of vertical shifts. The very small overlap in the confidence intervals indicates that the upper slope was slightly steeper for judgments of horizontal shifts of gaze than for judgments of vertical shifts. We also calculated the difference in the upper slope between horizontal and vertical shifts of gaze within each participant. The mean difference was 1.03 (95% CI = 0.23–2.51). The CI did not overlap 0, a result confirming that the upper slope was steeper for judgments of horizontal shifts of gaze.

Inspection of Fig. 5D suggests that for judgments of vertical shifts of gaze, the upper and lower slopes may have been slightly shallower for 4.8° shifts of gaze than for 8°. To investigate this possibility, we calculated the mean upper and lower slope separately for 4.8° and 8° vertical shifts of gaze. The lower slope was .17 (95% CI = −.29 to .41) for 4.8° shifts of gaze, and .23 (95% CI = −.04 to .67) for 8° shifts of gaze. The upper slope was −3.60 (95% CI = −4.55 to −2.73) for 4.8° shifts of gaze, and −3.67 (95% CI = −3.98 to −3.40) for 8° shifts of gaze. The considerable overlap in the confidence intervals indicates that there was no significant difference in the upper and lower slopes between 4.8° and 8° vertical shifts of gaze.

The steeper lower and upper slopes observed for judgments of horizontal shifts of gaze than for vertical shifts indicate that human observers made greater use of SFs above and below the breakpoint for vertical shifts of gaze. This pattern suggests that SF tuning is finer for judgments of horizontal shifts of gaze.

7. General discussion

7.1. Summary

The current study provides the first information on SF tuning for judgments of eye gaze, and on whether this tuning differs between judgments of facial identity and eye gaze. In Experiment 1, participants discriminated between leftward and rightward gaze, or between two male faces or two female faces. Masking with bandpass-filtered visual noise lead to the greatest disruption of human performance (i.e., the highest contrast threshold) at a higher SF for judgments of gaze (approximately 20 c/fw) than for judgments of facial identity (approximately 15 c/fw). After adjusting our estimates of human sensitivity to take into account the amount of visual information available to perform the task, low to mid SFs were most important for judgments of facial identity, with a sharp dropoff in importance above around 15 c/fw. A similar pattern was observed for judgments of facial identity in a previous study using a similar method (Gao & Maurer, 2011). In contrast, for judgments of horizontal shifts of gaze, SFs increased in importance from low to mid (approximately 16 c/fw) values, with a sharp dropoff in importance above around 20 c/fw. This pattern provides the first evidence that mechanisms underlying judgments of horizontal shifts of gaze make less use of information at low SFs than mechanisms underlying judgments of facial identity, and that the optimal band of SFs is higher for judgments of gaze than for identity.

In Experiment 2, participants discriminated between gaze shifted to the left/right or up/down. In each condition, masking lead to the poorest performance at 20 c/fw, a value similar to that observed for judgments of horizontal shifts of gaze in Experiment 1. After taking into account the amount of visual information available to perform the task, the highest SF important for human performance was the same for judgments of horizontal and vertical shifts of gaze (approximately 20 c/fw). However, the SFs above and below this peak were more important for judgments of vertical shifts of gaze than for judgments of horizontal shifts, a pattern that may reflect finer tuning for judgments of horizontal shifts of gaze.

7.2. Eye gaze and facial identity

Our results may provide information about the extent to which the visual system uses a common set of resources to process facial identity and eye gaze. Our finding that the optimal band of SFs was higher for eye gaze than for identity is consistent with the hypothesis that these two signals are processed by separate mechanisms (Hoffman & Haxby, 2000). However, we also found that relative sensitivity for both types of signals was much higher for low to mid SFs than it was for higher SFs (see Fig. 3D), and that the SF tuning functions for the two signals overlapped at around 16 c/fw. This partial overlap in SF tuning is consistent with the hypothesis that there is at least some functional overlap between mechanisms for processing facial identity and eye gaze (Baseler et al., 2014). The observed importance of low SFs for both identity and gaze could also reflect the involvement of a putative subcortical neural mechanism that is sensitive to both types of signals, and responds selectively to low SFs (Johnson, 2005; Senju & Johnson, 2009).

One plausible contributor to differences in SF tuning between facial identity and eye gaze is the perceptual relevance of fine details carried by mid to high SFs. Our finding that judgments of eye gaze are tuned to higher SFs than judgments of identity may reflect greater perceptual relevance of these fine details for discriminating the direction of gaze. Humans can reliably discriminate very small shifts of gaze (around 1–2°) (Bock, Dicke, & Thier, 2008; Symons et al., 2004; Vida & Maurer, 2012b). This ability requires sensitivity to subtle differences in the appearance of the eye (e.g., the position of the iris within the white sclera) (Anstis, Mayhew, & Morley, 1969; Symons et al., 2004), which may be carried primarily by high SFs (see Johnson, 2005). The importance of these high SFs for discriminating small shifts of gaze could lead adults to rely on relatively high SFs when discriminating this signal, even for relatively large shifts of gaze such as those presented in the current study (4.8° and 8°).

Humans can use several different visual cues to discriminate facial identity, including the spacing among facial features, and the shapes of facial features (see Maurer, Le Grand, & Mondloch, 2002; but also see Taschereau-Dumouchel et al., 2010). Spacing cues appear to be more easily seen with low SFs, whereas shape cues are more easily seen with high SFs (Goffaux et al., 2005). Given that humans can use low SFs to efficiently discriminate at least some cues to facial identity, it may not be necessary for mechanisms for processing facial identity to be tuned to SFs as high as those used for discriminating the direction of gaze.

7.3. Horizontal and vertical shifts of gaze

The finding in Experiment 2 that the slopes of the relative sensitivity function were steeper for judgments of horizontal shifts of gaze than for judgments of vertical shifts (see Fig. 5D) provides the first evidence that SF tuning is finer for horizontal shifts of gaze. This finding contrasts with previous findings of similar SF tuning for judgments of several different pairs of facial expressions (Gao & Maurer, 2011). Together, our results and those of Gao and Maurer (2011) suggest that SF tuning differs between different types of changeable facial signals.

The difference in SF tuning between horizontal and vertical shifts of gaze may reflect differences in experience. In many environments, potential targets of gaze are distributed more densely along the horizontal axis than along the vertical axis. Hence, we speculate that individuals may receive more experience with others shifting their gaze along the horizontal axis than along the vertical axis. Experience with broadband visual stimuli can affect spatial frequency tuning in several different ways, such as increased reliance on low SFs in object perception (Caplette et al., 2014), and a boost in contrast sensitivity at SFs above 3 c/degree Li et al., 2009. Greater experience with horizontal shifts of gaze could potentially lead to a shift of SF tuning toward the optimal SF band for processing this signal, a shift that might lead to more efficient processing by reducing reliance on less useful SFs above and below the optimal SF.

Finer SF tuning for horizontal shifts of gaze could also reflect differences in visual cues for horizontal and vertical shifts of gaze. Both horizontal and vertical shifts of gaze involve changes in the apparent position of the iris within the eye region. For horizontal shifts, these changes are signalled by the horizontal position of the iris within the surrounding white sclera. In contrast, vertical shifts of gaze involve complex and vertically asymmetrical changes in the positions of the iris, eyelids, and/or eyebrows (Anstis, Mayhew, & Morley, 1969; Bock, Dicke, & Thier, 2008). For example, the upper eyelid closely tracks the vertical position of the iris, whereas the lower eyelid does not. As a result, the eye typically opens wider when a person looks up, and becomes more closed when a person looks down. Across all four models in Experiment 2, the vertical distance between the upper and lower eyelids increased by 14.0% ($SD = 5.5\%$) when gaze shifted 8° upward from vertical meridian, and this distance decreased by 9.9% ($SD = 4.9\%$) when gaze shifted 8° downward. The opening of the eye for upward shifts of gaze can expose more of the lower part of the iris and the sclera under the iris, whereas the closure of the eye for downward shifts of gaze can occlude more of these parts of the eye. Given the relative complexity of visual cues to vertical shifts of gaze, it seems possible that precise judgments of vertical shifts of gaze would require sensitivity to a larger set of visual cues than judgments of horizontal shifts of gaze, a difference that may necessitate tuning to a broader range of SFs for vertical shifts of gaze.

It is important to note that the two accounts described above are not mutually exclusive. For example, it is possible that greater experience with horizontal shifts of gaze could lead to greater knowledge of the spatial dynamics of visual cues specific to horizontal shifts of gaze, and could thereby allow more efficient sampling of visual information (e.g., increased sampling of useful information in mid SFs, decreased sampling of less useful information in high and low SFs) for horizontal shifts of gaze.

7.4. Future research

One remaining question is whether SF tuning for judgments of eye gaze would have differed if participants had been asked to make judgments of direct and averted gaze instead of the judgments of leftward/rightward or upward/downward gaze made in the current study. A subcortical neural mechanism may support rapid detection of direct gaze based on low SF information (Senju & Johnson, 2009). Such a mechanism could lead to greater efficiency in discriminating between direct and averted gaze than in making other types of judgments of gaze (e.g., the judgments of leftward/rightward and upward/downward shifts of gaze made in the current study) when faces are presented with low SFs only. Future studies could investigate this possibility by measuring speed and accuracy for several types of judgments of gaze (e.g., direct and averted gaze, leftward and rightward gaze) in faces filtered to include a series of narrow SF bands.

7.5. Conclusions

The current study provides the first information on SF tuning for judgments of eye gaze, and provides the first comparison of SF tuning for facial identity and gaze. In Experiment 1, participants discriminated between gaze shifted to the left or right, or between two male faces or two female faces. For judgments of identity, information at low to mid SFs was most important. For gaze, information at mid to high SFs was most important, and the highest SF important for gaze was higher than that for identity. In Experiment 2, participants discriminated horizontal and vertical shifts of gaze. The highest SF important for judgments of gaze was similar to that for judgments of gaze in Experiment 1. However, lower and higher SFs surrounding the peak were more important for judgments of vertical shifts of gaze than for horizontal shifts of gaze. These results provide the first evidence that mechanisms underlying judgments of eye gaze are tuned to higher SFs than those underlying judgments of identity, and that this tuning is finer for horizontal than for vertical shifts of gaze.

Acknowledgement

This research was supported by a Natural Sciences and Engineering Research Council (NSERC) Vanier Canada Graduate Scholarship (CGS-V) to MDV, a Margo Wilson and Martin Daly Ontario Graduate Scholarship (OGS) to MDV, and a grant from NSERC (9797) to DM. A preliminary version of the results was presented at the 2014 annual meeting of the Vision Sciences Society (VSS).

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.visres.2015.04.018.

References

Anstis, S. M., Mayhew, J. W., & Morley, T. (1969). The perception of where a face or television portrait is looking. *American Journal of Psychology, 82*, 474–489.
Argyle, M., & Cook, M. (1976). *Gaze and mutual gaze*. New York: Cambridge University Press.
Banks, M. S., & Salapatek, P. (1978). Acuity and contrast sensitivity in 1-, 2-, and 3-month-old human infants. *Investigative Opthalmology and Vision Science, 17*, 361–365.
Baseler, H. A., Harris, R. J., Young, A. W., & Andrews, T. J. (2014). Neural responses to expression and gaze in the posterior superior temporal sulcus interact with facial identity. *Cerebral Cortex, 24*, 737–744.
Bock, S. W., Dicke, P., & Thier, P. (2008). How precise is gaze following in humans? *Vision Research, 48*, 946–957.
Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision, 10*, 433–439.
Caplette, L., West, G. L., Wicker, B., Gomot, M., & Gosselin, F. (2014). Action video game exposure modulates spatial frequency tuning for emotional objects. *Journal of Vision, 14*.
Costen, N. P., Parker, D. M., & Craw, I. (1996). Effects of high-pass and low-pass spatial filtering on face identification. *Perception and Psychophysics, 58*, 602–612.
Emery, N. J. (2000). The eyes have it: The neuroethology, function and evolution of social gaze. *Neuroscience and Biobehavioral Reviews, 24*, 581–604.
Farroni, T., Csibra, G., Simion, F., & Johnson, M. H. (2002). Eye contact detection in humans from birth. *Proceedings of the National Academy of Sciences, 99*, 9602–9605.
Fiorentini, A., Maffei, L., & Sandini, G. (1983). The role of high spatial frequencies in face perception. *Perception, 12*, 195–201.
Ganel, T. (2011). Revisiting the relationship between the processing of gaze direction and the processing of facial expression. *Journal of Experimental Psychology: Human Perception and Performance, 37*, 48–57.
Gao, X., & Maurer, D. (2011). A comparison of spatial frequency tuning for the recognition of facial identity and facial expressions in children and adults. *Vision Research, 51*, 508–519.
Goffaux, V., Hault, B., Michel, C., Vuong, Q. C., & Rossion, B. (2005). The respective role of low and high spatial frequencies in supporting configural and featural processing of faces. *Perception, 34*, 77–86.
Goffaux, V., & Rossion, B. (2006). Faces are spatial–holistic face perception is supported by low spatial frequencies. *Journal of Experimental Psychology: Human Perception and Performance, 32*, 1023–1039.
Gold, J., Bennett, P. J., & Sekuler, A. B. (1999). Identification of band-pass filtered letters and faces by human and ideal observers. *Vision Research, 39*, 3537–3560.
Hayes, T., Morrone, M. C., & Burr, D. C. (1986). Recognition of positive and negative bandpass-filtered images. *Perception, 15*, 595–602.
Hoffman, E. A., & Haxby, J. V. (2000). Distinct representations of eye gaze and identity in the distributed human neural system for face perception. *Nature Neuroscience, 3*, 80–84.
Johnson, M. H. (2005). Subcortical face processing. *Nature Reviews Neuroscience, 6*, 766–774.
Li, R., Polat, U., Makous, W., & Bavelier, D. (2009). Enhancing the contrast sensitivity function through action video game training. *Nature Neuroscience, 12*, 549–551.
Maurer, D., Le Grand, R. L., & Mondloch, C. J. (2002). The many faces of configural processing. *Trends in Cognitive Sciences, 6*, 255–260.
Muggeo, V. M. R. (2003). Estimating regression models with unknown break-points. *Statistics in Medicine, 22*, 3055–3071.
Näsänen, R. (1999). Spatial frequency bandwidth used in the recognition of facial images. *Vision Research, 39*, 3824–3833.
Norcia, A. M., & Tyler, C. W. (1985). Spatial frequency sweep vep: Visual acuity during the first year of life. *Vision Research, 25*, 1399–1408.
Norcia, A. M., Tyler, C. W., & Hamer, R. D. (1990). Development of contrast sensitivity in the human infant. *Vision Research, 30*, 1475–1486.
Ojanpää, H., & Näsänen, R. (2003). Utilisation of spatial frequency information in face search. *Vision Research, 43*, 2505–2515.
Prins, N., & Kingdom, F. A. A. (2009). *Psychophysics: A practical introduction*. Academic Press.
Senju, A., & Johnson, M. H. (2009). The eye contact effect: Mechanisms and development. *Trends in Cognitive Sciences, 13*, 127–134.
Symons, L. A., Lee, K., Cedrone, C. C., & Nishimura, M. (2004). What are you looking at? acuity for triadic eye gaze. *Journal of General Psychology, 131*, 451–469.
Taschereau-Dumouchel, V., Rossion, B., Schyns, P. G., & Gosselin, F. (2010). Interattribute distances do not represent the identity of real-world faces. *Frontiers in Psychology, 1*.
Tieger, T., & Ganz, L. (1979). Recognition of faces in the presence of two-dimensional sinusoidal masks. *Perception and Psychophysics, 26*, 163–167.
Tjan, B. S., Braje, W. L., Legge, G. E., & Kersten, D. (1995). Human efficiency for recognizing 3d objects in luminance noise. *Vision Research, 35*, 3053–3069.
Vida, M. D., & Maurer, D. (2012a). The development of fine-grained sensitivity to eye contact after 6 years of age. *Journal of Experimental Child Psychology, 112*, 243–256.
Vida, M. D., & Maurer, D. (2012b). Gradual improvement in fine-grained sensitivity to triadic gaze after age 6. *Journal of Experimental Child Psychology, 111*, 299–318.
Vida, M. D., & Maurer, D. (2013). I see what you're saying: Voice signals influence children's judgments of direct and averted gaze. *Journal of Experimental Child Psychology, 116*, 609–624.
Wang, Y., Fu, X., Johnston, R. A., & Yan, Z. (2013). Discriminability effect on Garner interference: Evidence from recognition of facial identity and expression. *Frontiers in Psychology*.