On the Perception of Bandlimited Phase Distortion in Natural Scenes

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ABSTRACT

It is widely believed that the phase spectrum of an image contributes much more to the image's visual appearance than the magnitude spectrum. Several researchers have also shown that this phase information can be computed indirectly from local magnitude information, a theory which is consistent with the physiological evidence that complex cells respond to local magnitude (and are insensitive to local phase). Recent studies have shown that tasks such as image recognition and categorization can be performed using only local magnitude information. These findings suggest that the human visual system (HVS) uses local magnitude to infer global phase (image-wide phase spectrum) and thereby determine the image's appearance. However, from a signal-processing perspective, both local magnitude and *local phase* are related to global phase. Moreover, in terms of image quality, distorting the local phase can result in a severely degraded image. These latter facts suggest that the HVS uses both local magnitude and local phase to determine an image's appearance. We conducted an experiment to quantify the contributions of local magnitude and local phase toward image appearance as a function of spatial frequency. Hybrid images were created via a complex wavelet transform in which the the low frequency magnitude, low frequency phase, high frequency magnitude, and high frequency phase were taken from 2-4 different images. Subjects were then asked to rate how much each of the 2-4 images contributed to the the appearance of the hybrid image. We found that local magnitude is indeed an important factor for image appearance; however, local phase can play an equally important role, and in some cases, local phase can dominate the image's appearance. We discuss the implication of these results in terms of image quality and visual coding.

Keywords: local phase distortion, importance of local phase, importance of local magnitude, global phase

1. INTRODUCTION

A wide body of research in both visual psychology and image processing has been performed to better understand the importance of phase and magnitude in image perception. In 1981 Oppenheim and Lim[1] demonstrated the importance of phase in signals. Oppenheim and Lim demonstrated that the phase spectrum conveys much more visual information about an image compared to the magnitude spectrum. However, primates V1 is dominated by complex cells.[2] These complex cells encode the magnitude information and are largely insensitive to the spatial phase information. This suggests that the phase is of lesser importance than the magnitude for the human visual system (HVS), which seems to contradict the belief that the phase information is more important than the magnitude information. One possible explanation for this apparent contradiction is to consider the fact that complex cells have localized receptive fields; thus, the phase may be implicitly encoded in the local magnitude.

Several researchers have demonstrated that the phase spectrum of an image can be computed from the local magnitude information (complex cell responses). Morrone and Burr[3] demonstrated that Gabor feature detectors are in-phase at the location of lines and edges. These are the locations where local energy is maximal, and thus it is possible to compute these phase-congruent locations given only the local magnitude information. Other researchers have shown that only the local magnitude information is required for tasks such as scene categorization, recognition, and/or general appearance.[4–7] Morgan *et al.*[4] demonstrated that phase is of lesser importance than magnitude when the image is analyzed locally. Morgan *et al.* subjected natural images to patch-wise Fourier analysis and swapped the local magnitude and the local phase between the patches of different images. They demonstrated that when the patch sizes were relatively large (e.g., 50% of the image size), the perception of the image was due primarily to the phase. However, for relatively smaller patch sizes (e.g., 2% of

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the image size), the perception of the image was due primarily to the magnitude. In terms of visual processing, these findings suggest that the HVS uses the local magnitude information to determine the global (image-wide) phase information; thus, an image's apperance is determined indirectly by the local magnitude (i.e., as shown by Oppenheim and Lim, the global phase spectrum determines image's appearance, and as shown by the researchers mentioned here, the local magnitude spectra determines the global phase).

Despite the fact that the global phase (and thus appearance) of an image can be inferred from the local magnitude, there remains the question of why the visual system would take such an indirect approach. It is widely believed that complex cells compute the local magnitude by combining the responses of two simple cells. However, there may exist some other visual mechanism which also utilizes the responses from simple cells to encode other perceptually relevant information such as the *local* phase. Indeed, there is no clear evidence which refutes the possibility that the responses of simple cells are also provided directly to other visual areas (e.g., V2) without being first processed by the complex cells. From a signal-processing perspective, local phase also plays an important role in the representation of images. If the HVS uses only local magnitude information for perception, then distortion of local phase should not have much of an impact on the appearance of an image.

However, subjecting images to local-phase-only distortion does indeed have a major effect on image quality. We generated distorted images by adding Gaussian noise to only the local phase spectrum by using a complex wavelet transform. Addition of the noise to the local phase had a major effect on the quality of the images. Figure 1 shows the effect of such local phase distortion. If the local phase is inferred from local magnitude, then distortion of the local phase should not have such a profound impact on the quality of the image. This example seems to suggest that there is some explicit mechanism to encode the local phase information.

(a) (b)

Figure 1. Effect of local phase distortion on image quality: (a) original image *balloon* and (b) local-phase-distorted *balloon*.

Here, we present the results of a study designed to test whether the global phase is inferred only from the local magnitude, or whether the global phase is also computed via another visual mechanism (e.g., by passing the simple-cell responses directly to some other visual mechanism). By using a complex wavelet transform, we created hybrid images in which the local magnitude information came from one image (say, Image A) and the local phase information came from another image (say, Image B). If the HVS infers global phase only from the local magnitude, then the resulting hybrid image should look only like the image from which the local magnitude was used (Image A). On the other hand, if the global phase is inferred from *both* the local magnitude and the local phase, then the resulting hybrid image should look like both images.

We conducted a psychophysical experiment which used such hybrid images to measure the relative contributions of local magnitude and local phase toward image appearance. Images were subjected to a four-level complex wavelet transform (CWT) which allowed us to separate local magnitude from local phase within different frequency bands. Hybrid images were created by performing an inverse CWT on subbands created via combinations of local magnitude and local phase derived from 2-4 different images. This scheme allowed us to investigate the relative contributions of local magnitude and local phase as a function of spatial frequency.* Based on the permutations to make the hybrid in complex wavelet coefficients, 14 combinations were created. In each combination, relative importance of local magnitude and local phase in high and low spatial frequency ranges were computed. In a second experiment, we asked human subjects to rate the visual qualities of images containing various amounts of bandlimited phase distortion. Based on these results, we present an algorithm, Local magnitude Phase Distortion Rater (LMPD), which attempts to predict the visual quality of phase-distorted images. We also compare our algorithm against a variety of modern image quality assessment algorithms.

2. METHODS

A psychophysical experiment was performed to measure the relative contributions of local magnitude and local phase in high and low spatial frequency bands toward image appearance. Images were decomposed into four complex wavelet subbands. The subbands were grouped into two spatial frequency ranges (high and low) based on each subband's center spatial frequency. The complex wavelets were generated using Hilbert-pair wavelet filters. This filterbank is shift-invariant, oriented, does not introduce any redundancy,[8] and is nearly perfect-reconstruction. Five adult subjects participated in the experiment including the first author.

2.1 Stimuli

Hybrid image stimuli were generated using four commonplace images (*kid*, *girl*, *duck*, and *sealion*). The images were of size 384×384 pixels and were 8-bit grayscale with pixel values in the range $0 - 255$. Figure 2 shows the original images used in the experiment. These images were then decomposed into four complex wavelet subbands. Hybrid images were created by forming the four complex wavelet subbands, where each subband's local magnitude and local phase in all orientations was taken from the local magnitude and the local phase of the complex wavelet subbands of four original images. Using these hybrid complex wavelet subbands, an inverse CWT was performed to obtain the stimuli.

Given two bands, two types of information (magnitude and phase), and four source images, there are 14 different ways in which the hybrid image stimuli can be created. These combinations are as follows:

- Combination 1: The stimuli were created by using the local magnitude and the local phase in high and low spatial frequency subbands from the four different images.
- Combination 2: The stimuli were created by using local magnitude in low and high spatial frequency subbands from an image and local phase in low and high spatial frequency subbands from two different images.
- Combination 3: The stimuli were created by using local phase in low and high spatial frequency subbands from an image and local magnitude in low and high spatial frequency subbands from two different images.
- Combination 4: The stimuli were created by using local magnitude and local phase in low spatial frequency subbands from an image and local magnitude and local phase in high spatial frequency subbands from two different images.
- Combination 5: The stimuli were created by using local magnitude and local phase in high spatial frequency subbands from the same image and local magnitude and local phase in low spatial frequency subbands from two different images.
- Combination 6: The stimuli were created by using local magnitude in low spatial frequency subbands and local phase in high spatial frequency subbands from an image and local magnitude in high spatial frequency subbands and local phase in low spatial frequency subbands from two different images.
- Combination 7: The stimuli were created by using local magnitude in high spatial frequency subbands and local phase in low spatial frequency subbands from an image and local magnitude in low spatial frequency subbands and local phase in high spatial frequency subbands from two different images.

*Morgan's[4] experiment demonstrated the importance of local phase and local magnitude over the patch size of Fourier analysis. The experiment presented in this paper is different from Morgan's experiment because it allows us to look at the relative importance of local phase and local magnitude as a function of spatial frequency.

- Combination 8: The stimuli were created by using local magnitude of low and high spatial frequency subbands and local phase of low spatial frequency subbands from an image and local phase of high spatial frequency subbands from another image.
- Combination 9: The stimuli were created by using local magnitude of low and high spatial frequency subbands and local phase of high spatial frequency subbands from an image and local phase of low spatial frequency subbands from another image.
- Combination 10: The stimuli were created by using local magnitude of low spatial frequency subbands and local phase of low and high spatial frequency subbands from an image and local magnitude of high spatial frequency subbands from another image.
- Combination 11: The stimuli were created by using local magnitude of high spatial frequency subbands and local phase of low and high spatial frequency subbands from an image and local magnitude of low spatial frequency subbands from another image.
- Combination 12: The stimuli were created by using local magnitude in high and low spatial frequency subbands from an image and local phase in low and high spatial frequency subbands from another image.
- Combination 13: The stimuli were created by using local magnitude and local phase in low spatial frequency subbands from an image and local magnitude and local phase in high spatial frequency subbands from another image.
- Combination 14: The stimuli were created by using local magnitude of low spatial frequency subbands and local phase of high spatial frequency subbands from an image and local magnitude of high spatial frequency subbands and local phase of low spatial frequency subbands from another image.

Twelve hybrid images were created for each of the above 14 combinations. Thus, a total of $12 \times 14 = 168$ stimuli were used in the experiment. See Section 3 for example images used for each particular combination.

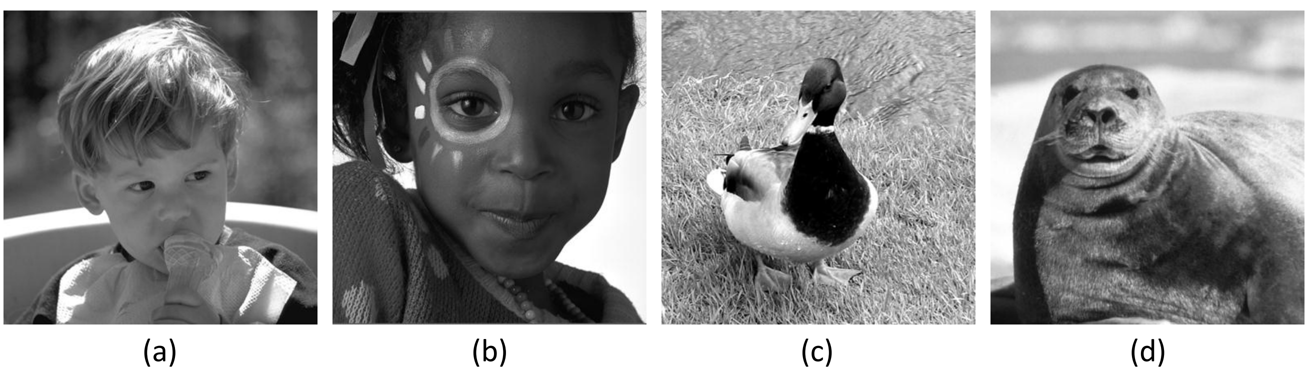


Figure 2. Original images used in the experiment (a) *kid*, (b) *girl*, (c) *duck* and (d) *sealion*.

2.2 Apparatus

Stimuli were displayed on an HP LP246 monitor. The screen size of the monitor was 24 inches at a display resolution of 36.9 pixels/cm, and a frame rate of 59.7 Hz. The display yielded minimum, maximum and mean luminance of 0.38, 303 and 85.9 cd/m2, respectively and a overall gamma of 2.235. Stimuli were viewed binocularly through natural pupils at a distance of approximately 60 cm.

2.3 Procedures

Contributions of local magnitude and local phase in high and low spatial frequency subbands of complex wavelet subbands were estimated for each combination by displaying 12 stimuli, one at a time, to each subject. Each stimulus was shown towards the top of the screen. Below the stimulus, the four original images were displayed. For each stimulus (hybrid image), subjects were asked to rate how much each original image contributed to the appearance of the stimulus. Graphical sliders were given for the subjects to rate the contribution of each image on a scale from 0% to 100%. The sliders were designed such that the subjects could not exceed a total of 100%.

Each subject rated all 12 stimuli for all 14 combinations. The average percentage of images contributing in local magnitude and local phase in high and low spatial frequency subbands were computed by normalizing each subject's score and then averaging over all subjects. Normalization was performed by dividing each components (here components refer to local phase and local magnitude in low and high spatial frequency) contribution by the sum of the contribution in all components. The resulting average of normalized percentage for each combination is the measure for the contribution of the local magnitude and the local phase in the high and low spatial frequency subbands for the perception of recognizable structures in the stimuli.

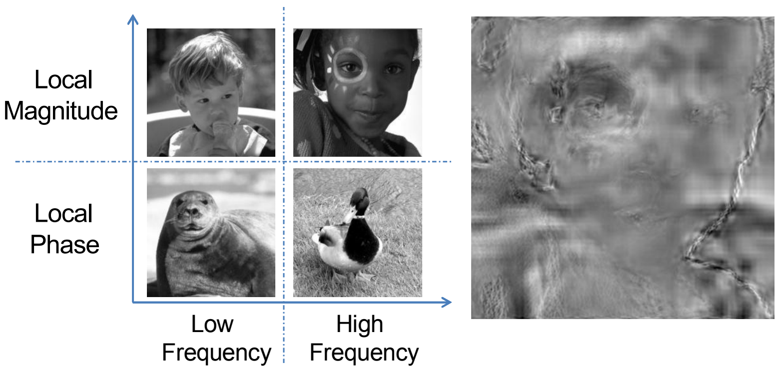
3. RESULTS

3.1 Analysis

The following are the results obtained from the experiment for each combination.

3.1.1 Combination 1

Figure 3 shows the arrangement of complex wavelet coefficients, the hybrid image created and the Table shows the contribution of local magnitude and local phase in high and low spatial frequency subbands in percentage and standard deviation amongst the subjects. In this table ML refers to local magnitude from low spatial frequency subbands, MH refers to local magnitude from high spatial frequency subbands, PL refers to local phase from low spatial frequency subbands and PH refers to local phase from high spatial frequency subbands. These results show that when high and low spatial frequency subbands do not cooperate (i.e., not from the same image) and local magnitude and local phase also do not cooperate, then the HVS relies on high spatial frequency local magnitude more than anything else.



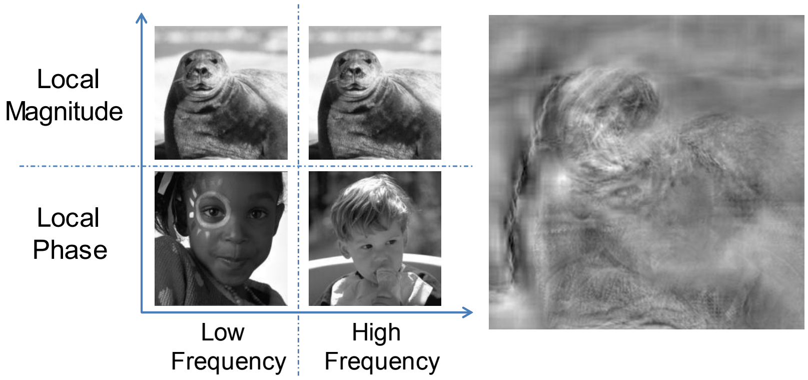
	ML	MH	PL	PH
Contrib.	6%	59%	8%	27%
STD	7%	11%	4%	6%

(a) (b) (c)

Figure 3. Combination 1 hybrid image and the result. (a) shows the combination of complex wavelet coefficient's local magnitude and local phase in low and high spatial frequencies to form hybrid image. (b) shows the hybrid image for the the combination in (a). Table(c) shows contribution (Contrib.) of local magnitude in low spatial frequency(ML), local magnitude in high spatial frequency(MH), local phase in low spatial frequency(PL) and local phase in high spatial frequency(PH) to the image appearance and standard deviation (STD) amongst five subjects.

3.1.2 Combination 2

Figure 4 shows the arrangement of complex wavelet coefficients, the hybrid image created, and the Table shows the contribution of local magnitude and local phase in high and low spatial frequency subbands in percentage and standard deviation amongst the subjects. In this table ML/MH refers to local magnitude in low and high spatial frequency. Local magnitude in low and high spatial frequency subbands are combined because they are from the same image. These results show that when local magnitude in high and low spatial frequency subbands cooperate, then the HVS relies on the local magnitude more than the local phase.



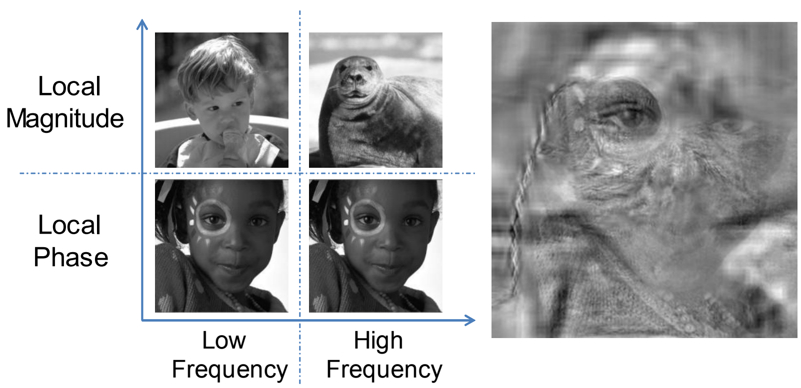
	ML/MH	PL	PH
Contrib.	65%	8%	27%
STD	9%	6%	3%

(a) (b) (c)

Figure 4. Combination 2 hybrid image and the result. (a) shows the combination of complex wavelet coefficient's local magnitude and local phase in low and high spatial frequencies to form hybrid image. (b) shows the hybrid image for the the combination in (a). Table(c) shows contribution (Contrib.) of local magnitude in low spatial frequency(ML), local magnitude in high spatial frequency(MH), local phase in low spatial frequency(PL) and local phase in high spatial frequency(PH) to the image appearance and standard deviation (STD) amongst five subjects.

3.1.3 Combination 3

Figure 5 shows the arrangement of complex wavelet coefficients, the hybrid image created, and the Table shows the contribution of local magnitude and local phase in high and low spatial frequency subbands in percentage and standard deviation amongst the subjects. In this table PL/PH refers to local phase in low and high spatial frequency. Local phase in low and high spatial frequency subbands are combined because they are from the same image. These results show that when local phase in high and low spatial frequency subbands cooperate, then the HVS relies on local phase more than the local magnitude information. However, contribution of high spatial frequency local magnitude is also substantial.



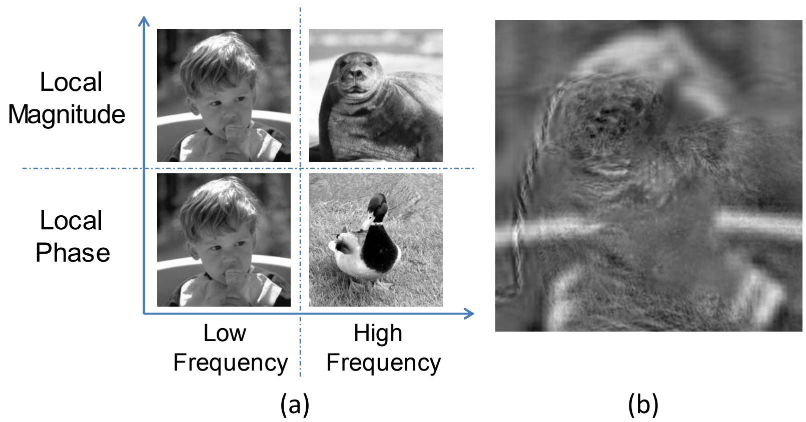
	PL/PH	ML	MH
Contrib.	55%	6%	39%
STD	3%	4%	1%

(a) (b) (c)

Figure 5. Combination 3 hybrid image and the result. (a) shows the combination of complex wavelet coefficient's local magnitude and local phase in low and high spatial frequencies to form hybrid image. (b) shows the hybrid image for the the combination in (a). Table(c) shows contribution (Contrib.) of local magnitude in low spatial frequency(ML), local magnitude in high spatial frequency(MH), local phase in low spatial frequency(PL) and local phase in high spatial frequency(PH) to the image appearance and standard deviation (STD) amongst five subjects.

3.1.4 Combination 4

Figure 6 shows the arrangement of complex wavelet coefficients, the hybrid image created, and the Table shows the contribution of local magnitude and local phase in high and low spatial frequency subbands in percentage and standard deviation amongst subjects. In this table ML/PL refers to local magnitude and local phase in low spatial frequency. Local magnitude and local phase in low spatial frequency subbands are combined because they are from the same image. These results show that when local magnitude and local phase in low spatial frequency subbands cooperate, then the HVS relies on cooperating low spatial frequency subbands more than anything else. However, contribution of high spatial frequency local magnitude is also substantial.



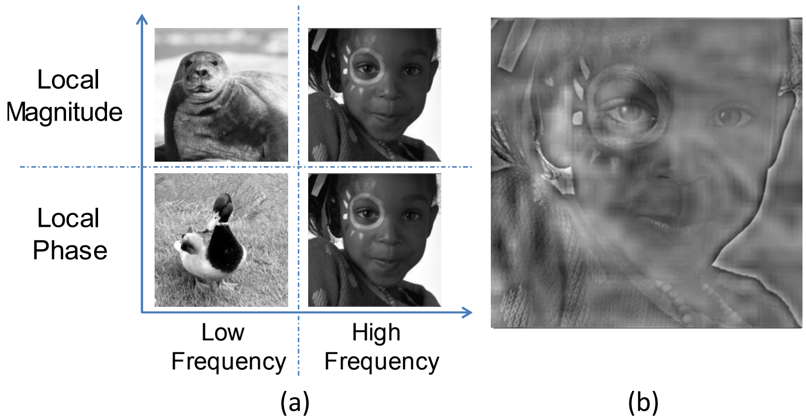
(c)

	ML/PL	MH	PH
Contrib.	44%	38%	18%
STD	3%	3%	3%

Figure 6. Combination 4 hybrid image and the result. (a) shows the combination of complex wavelet coefficient's local magnitude and local phase in low and high spatial frequencies to form hybrid image. (b) shows the hybrid image for the the combination in (a). Table(c) shows contribution (Contrib.) of local magnitude in low spatial frequency(ML), local magnitude in high spatial frequency(MH), local phase in low spatial frequency(PL) and local phase in high spatial frequency(PH) to the image appearance and standard deviation (STD) amongst five subjects.

3.1.5 Combination 5

Figure 7 shows the arrangement of complex wavelet coefficients, the hybrid image created, and the Table shows the contribution of local magnitude and local phase in high and low spatial frequency subbands in percentage and standard deviation amongst the subjects. In this table MH/PH refers to local magnitude and local phase in high spatial frequency. Local magnitude and local phase in high spatial frequency subbands are combined because they are from the same image. These results show that when local magnitude and local phase in high spatial frequency subbands cooperate, then the HVS relies on high spatial frequency subbands more than anything else.



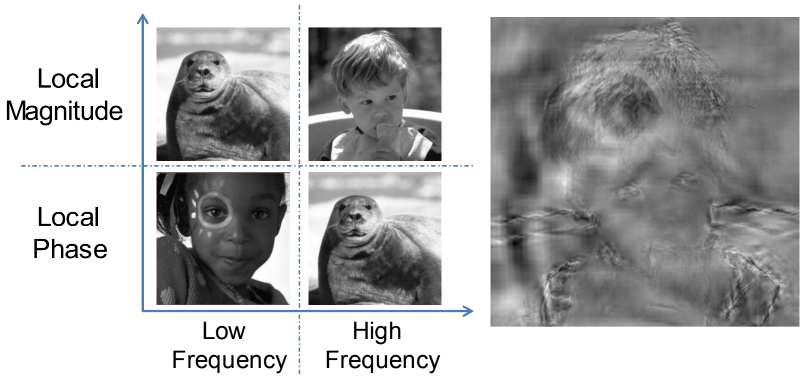
(c)

	MH/PH	ML	PL
Contrib.	87%	7%	6%
STD	12%	8%	5%

Figure 7. Combination 5 hybrid image and the result. (a) shows the combination of complex wavelet coefficient's local magnitude and local phase in low and high spatial frequencies to form hybrid image. (b) shows the hybrid image for the the combination in (a). Table(c) shows contribution (Contrib.) of local magnitude in low spatial frequency(ML), local magnitude in high spatial frequency(MH), local phase in low spatial frequency(PL) and local phase in high spatial frequency(PH) to the image appearance and standard deviation (STD) amongst five subjects.

3.1.6 Combination 6

Figure 8 shows the arrangement of complex wavelet coefficients, the hybrid image created, and the Table shows the contribution of local magnitude and local phase in high and low spatial frequency subbands in percentage and standard deviation amongst the subjects. Here in table ML/PH refers to local magnitude in low spatial frequency and local phase in high spatial frequency. Local magnitude in low and local phase in high spatial frequency subbands are combined because they are from the same image. These results show that when local magnitude in low spatial frequency subbands and local phase in high spatial frequency subbands cooperate, then the HVS relies more on local magnitude from high spatial frequency subbands than the cooperating subbands.



	ML/PH	MH	PL
Contrib.	39%	56%	6%
STD	2%	6%	6%

(a) (b) (c)

Figure 8. Combination 6 hybrid image and the result. (a) shows the combination of complex wavelet coefficient's local magnitude and local phase in low and high spatial frequencies to form hybrid image. (b) shows the hybrid image for the the combination in (a). Table(c) shows contribution (Contrib.) of local magnitude in low spatial frequency(ML), local magnitude in high spatial frequency(MH), local phase in low spatial frequency(PL) and local phase in high spatial frequency(PH) to the image appearance and standard deviation (STD) amongst five subjects.

3.1.7 Combination 7

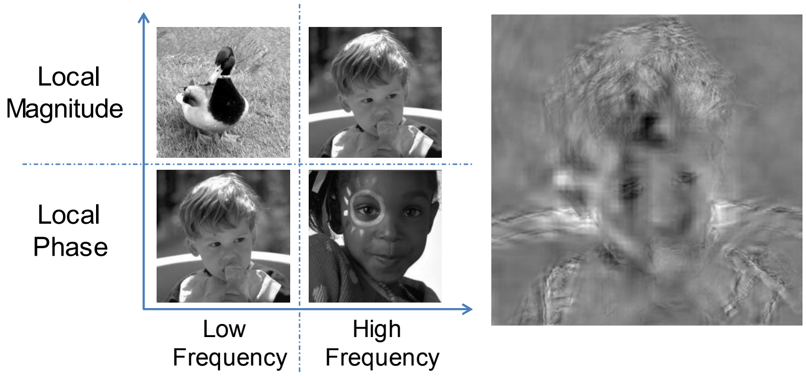
Figure 9 shows the arrangement of complex wavelet coefficients, the hybrid image created, and the Table shows the contribution of local magnitude and local phase in high and low spatial frequency subbands in percentage and standard deviation amongst the subjects. Here in table MH/PL refers to local magnitude in high spatial frequency and local phase in low spatial frequency. Local magnitude in high spatial frequency subbands and local phase in low spatial frequency subbands are combined because they are from the same image. These results show that when local magnitude in high spatial frequency subbands and local phase in low spatial frequency subbands cooperate, then the HVS relies on cooperating information more.

3.1.8 Combination 8

Figure 10 shows the arrangement of complex wavelet coefficients, the hybrid image created, and the Table shows the contribution of local magnitude and local phase in high and low spatial frequency subbands in percentage and standard deviation amongst the subjects. Here in table ML/MH/PL refers to local magnitude in low and high spatial frequency and local phase in low spatial frequency. Local magnitude from low and high spatial frequency subbands and local phase in low spatial frequency subbands are combined because they are from the same image. These results show that when local magnitude in low and high spatial frequency subbands and local phase in low spatial frequency subbands cooperate, then the HVS relies on cooperating information subbands more.

3.1.9 Combination 9

Figure 11 shows the arrangement of complex wavelet coefficients, the hybrid image created, and the Table shows the contribution of local magnitude and local phase in high and low spatial frequency subbands in percentage and standard deviation amongst the subjects. Here in table ML/MH/PH refers to local magnitude in low and

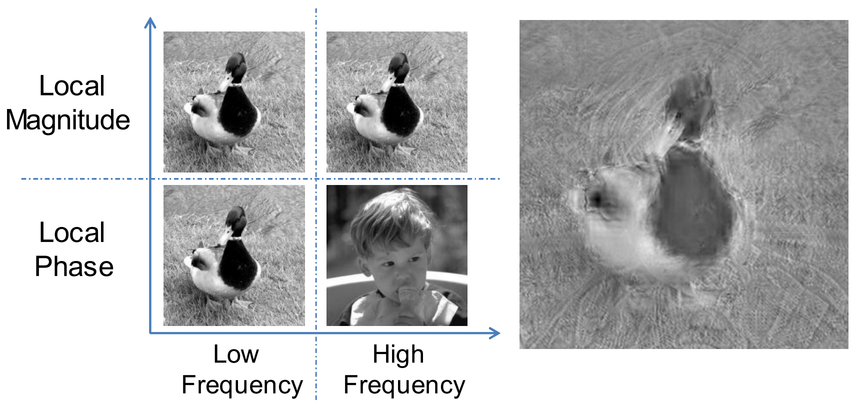


(a) (b)

	MH/PL	ML	PH
Contrib.	69%	5%	25%
STD	7%	6%	4%

(c)

Figure 9. Combination 7 hybrid image and the result. (a) shows the combination of complex wavelet coefficient's local magnitude and local phase in low and high spatial frequencies to form hybrid image. (b) shows the hybrid image for the the combination in (a). Table(c) shows contribution (Contrib.) of local magnitude in low spatial frequency(ML), local magnitude in high spatial frequency(MH), local phase in low spatial frequency(PL) and local phase in high spatial frequency(PH) to the image appearance and standard deviation (STD) amongst five subjects.



(a) (b)

	ML/MH/PL	PH
Contrib.	81%	19%
STD	3%	3%

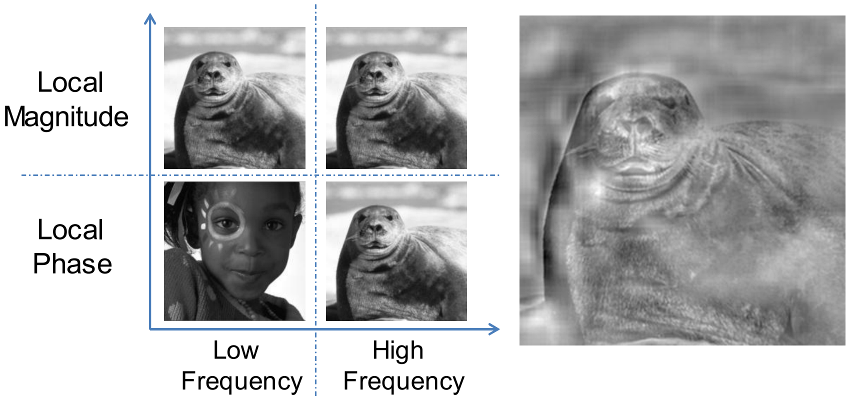
(c)

Figure 10. Combination 8 hybrid image and the result. (a) shows the combination of complex wavelet coefficient's local magnitude and local phase in low and high spatial frequencies to form hybrid image. (b) shows the hybrid image for the the combination in (a). Table(c) shows contribution (Contrib.) of local magnitude in low spatial frequency(ML), local magnitude in high spatial frequency(MH), local phase in low spatial frequency(PL) and local phase in high spatial frequency(PH) to the image appearance and standard deviation (STD) amongst five subjects.

high spatial frequency and local phase in high spatial frequency. Local magnitude from low and high spatial frequency subbands and local phase in high spatial frequency subbands are combined because they are from the same image. These results show that when local magnitude in low and high spatial frequency subbands and local phase in high spatial frequency subbands cooperate, then the HVS relies on cooperating information subbands more.

3.1.10 Combination 10

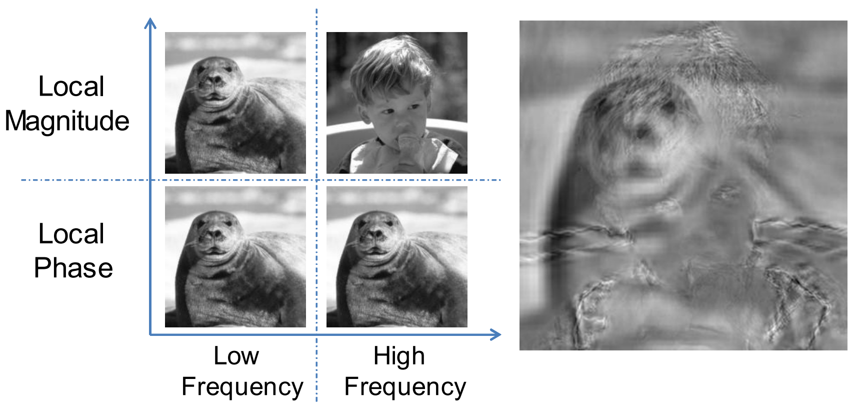
Figure 12 shows the arrangement of complex wavelet coefficients, the hybrid image created, and the Table shows the contribution of local magnitude and local phase in high and low spatial frequency subbands in percentage and standard deviation amongst the subjects. Here in table ML/Pl/PH refers to local magnitude in low spatial frequency and local phase in low and high spatial frequency. Local magnitude from low spatial frequency subbands and local phase in low and high spatial frequency subbands are combined because they are from same image. These results show that when local magnitude in low spatial frequency subbands and local phase in low and high spatial frequency subbands cooperate, then the HVS relies on cooperating information subbands more.



(a) (b) (c)

	ML/MH/PH	PL
Contrib.	94%	6%
STD	7%	7%

Figure 11. Combination 9 hybrid image and the result. (a) shows the combination of complex wavelet coefficient's local magnitude and local phase in low and high spatial frequencies to form hybrid image. (b) shows the hybrid image for the the combination in (a). Table(c) shows contribution (Contrib.) of local magnitude in low spatial frequency(ML), local magnitude in high spatial frequency(MH), local phase in low spatial frequency(PL) and local phase in high spatial frequency(PH) to the image appearance and standard deviation (STD) amongst five subjects.



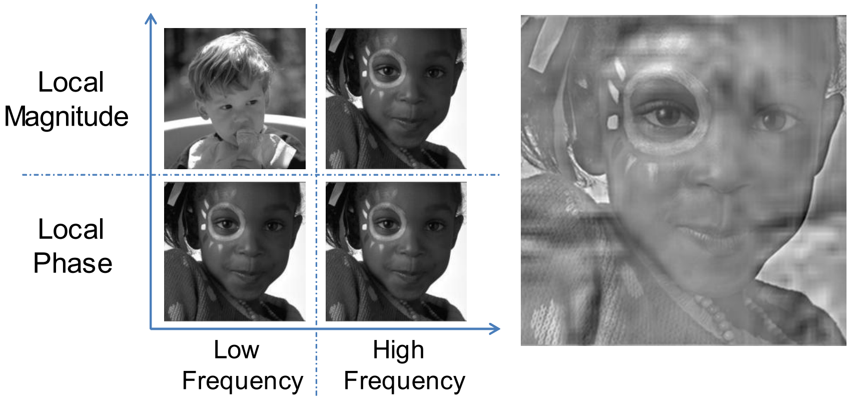
(a) (b) (c)

	ML/PL/PH	MH
Contrib.	74%	26%
STD	7%	7%

Figure 12. Combination 10 hybrid image and the result. (a) shows the combination of complex wavelet coefficient's local magnitude and local phase in low and high spatial frequencies to form hybrid image. (b) shows the hybrid image for the the combination in (a). Table(c) shows contribution (Contrib.) of local magnitude in low spatial frequency(ML), local magnitude in high spatial frequency(MH), local phase in low spatial frequency(PL) and local phase in high spatial frequency(PH) to the image appearance and standard deviation (STD) amongst five subjects.

3.1.11 Combination 11

Figure 13 shows the arrangement of complex wavelet coefficients, the hybrid image created, and the Table shows the contribution of local magnitude and local phase in high and low spatial frequency subbands in percentage and standard deviation amongst the subjects. Here in table MH/PL/PH refers to local magnitude in high spatial frequency and local phase in low and high spatial frequency. Local magnitude from high spatial frequency subbands and local phase in low and high spatial frequency subbands are combined because they are from the same image. These results show that when local magnitude in high spatial frequency subbands and local phase in low and high spatial frequency subbands cooperate, then the HVS relies on cooperating information subbands more.



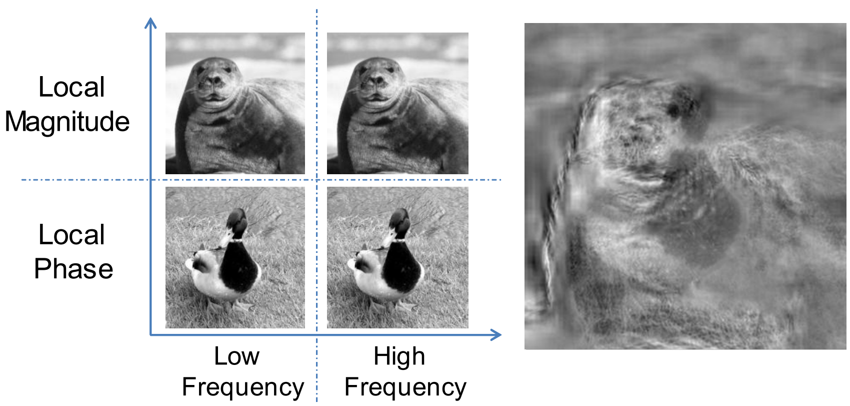
	MH/PL/PH	ML
Contrib.	98%	2%
STD	3%	3%

(a) (b) (c)

Figure 13. Combination 11 hybrid image and the result. (a) shows the combination of complex wavelet coefficient's local magnitude and local phase in low and high spatial frequencies to form hybrid image. (b) shows the hybrid image for the the combination in (a). Table(c) shows contribution (Contrib.) of local magnitude in low spatial frequency(ML), local magnitude in high spatial frequency(MH), local phase in low spatial frequency(PL) and local phase in high spatial frequency(PH) to the image appearance and standard deviation (STD) amongst five subjects.

3.1.12 Combination 12

Figure 14 shows the arrangement of complex wavelet coefficients, the hybrid image created, and the Table shows the contribution of local magnitude and local phase in high and low spatial frequency subbands in percentage and standard deviation amongst the subjects. These results show that when local magnitude cooperates in low and high spatial frequency subbands and local phase cooperates in low and high spatial frequency subbands, then the HVS relies on both local magnitude and local phase suggesting are equally important.



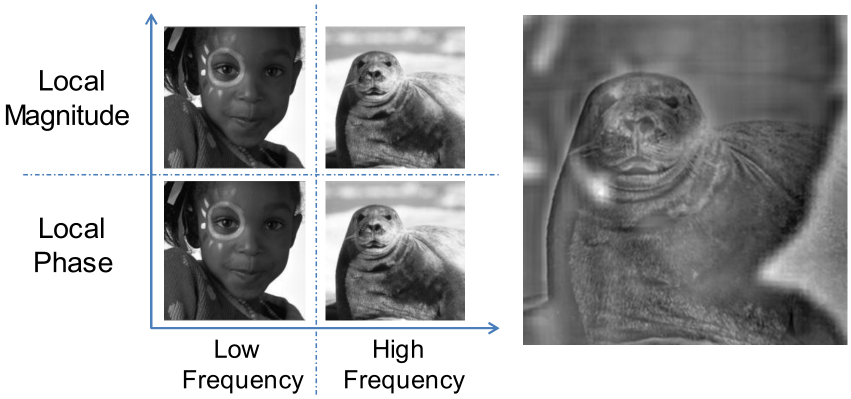
	ML/MH	PL/PH
Contrib.	48%	52%
STD	2%	2%

(a) (b) (c)

Figure 14. Combination 12 hybrid image and the result. (a) shows the combination of complex wavelet coefficient's local magnitude and local phase in low and high spatial frequencies to form hybrid image. (b) shows the hybrid image for the the combination in (a). Table(c) shows contribution (Contrib.) of local magnitude in low spatial frequency(ML), local magnitude in high spatial frequency(MH), local phase in low spatial frequency(PL) and local phase in high spatial frequency(PH) to the image appearance and standard deviation (STD) amongst five subjects.

3.1.13 Combination 13

Figure 15 shows the arrangement of complex wavelet coefficients, the hybrid image created, and the Table shows the contribution of local magnitude and local phase in high and low spatial frequency subbands in percentage and standard deviation amongst the subjects. These results show that when local magnitude and phase cooperates in low and high spatial frequency subbands, then the HVS relies more on high spatial frequency subbands than low spatial frequency subbands.



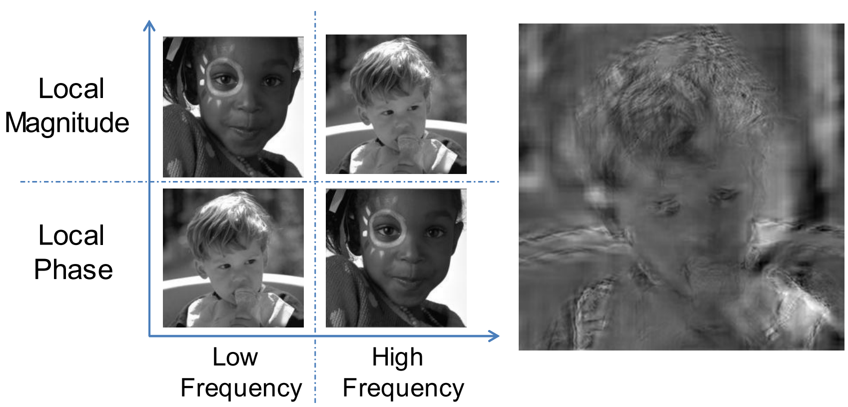
(a) (b) (c)

	ML/PL	MH/PH
Contrib.	24%	76%
STD	4%	4%

Figure 15. Combination 13 hybrid image and the result. (a) shows the combination of complex wavelet coefficient's local magnitude and local phase in low and high spatial frequencies to form hybrid image. (b) shows the hybrid image for the the combination in (a). Table(c) shows contribution (Contrib.) of local magnitude in low spatial frequency(ML), local magnitude in high spatial frequency(MH), local phase in low spatial frequency(PL) and local phase in high spatial frequency(PH) to the image appearance and standard deviation (STD) amongst five subjects.

3.1.14 Combination 14

Figure 16 shows the arrangement of complex wavelet coefficients, the hybrid image created, and the Table shows the contribution of local magnitude and local phase in high and low spatial frequency subbands in percentage and standard deviation amongst the subjects. These results show that when local magnitude from high spatial frequency and local phase from low spatial frequency cooperate and local magnitude from low spatial frequency and local phase from high spatial frequency cooperates, then the HVS relies mostly on high spatial frequency local magnitude and low spatial frequency local phase information more than the low spatial frequency local magnitude and high spatial frequency local phase information.



(a) (b) (c)

	MH/PL	ML/PH
Contrib.	71%	29%
STD	5%	5%

Figure 16. Combination 14 hybrid image and the result. (a) shows the combination of complex wavelet coefficient's local magnitude and local phase in low and high spatial frequencies to form hybrid image. (b) shows the hybrid image for the the combination in (a). Table(c) shows contribution (Contrib.) of local magnitude in low spatial frequency(ML), local magnitude in high spatial frequency(MH), local phase in low spatial frequency(PL) and local phase in high spatial frequency(PH) to the image appearance and standard deviation (STD) amongst five subjects.

3.2 Algorithm

From the overall results described in the previous section, we developed an algorithm called *Local Magnitude and Phase Distortion Rater* (LMPD), to rate the quality of local phase distorted images. LMPD computes both local magnitude distortion and the local phase distortion in an image and combines them to get a quality rating of a distorted image.

Local magnitude distortions were measured using local energy[9] on five frequency scales for both original image and distorted image. Algorithm to compute the local magnitude distortion is as follows:

1. Decompose original and distorted images in five scale and ten orientation log-Gabor subbands.
2. For each scale
   (a) Compute local energy maps of the original and distorted images.
   (b) Compute local MSE map between local energy maps of the original and distorted images. Use block size of 16×16 for local MSE.
   (c) Collapse local MSE map via the $L2 - norm$ into a single scalar value.
   (d) Compute correlation between local energy maps of original and distorted images.
   (e) Compute local magnitude distortion S_i(where, i is the index for current scale) by multiplying scalar values obtained in step (c) and (d).
3. Using Equation (1) combine the local magnitude distortion obtained for each scale in step (e) to compute local magnitude distortion rating in the distorted image.

$$localmagnitudeDistortionRating = (s_1^{p1}) + (s_2^{p2}) + (s_3^{p3}) + (s_4^{p4}) + (s_5^{p5}) \quad (1)$$

s_1, s_2, s_3, s_4 and s_5 are collapsed (via the L2 norm) values of local MSE map for five frequency scales. The quantities $p1$, $p2$, $p3$, $p4$, $p5$ are power coefficients with values of 4, 4, 2, 1.5 and 0.143 respectively. Values for power coefficients were selected empirically to roughly follow the experimental results.

Local phase distortions were measured using MSE between the local phase of the complex wavelet coefficients of original and distorted image. Algorithm to compute the local phase distortion is as follows:

1. Decompose original and distorted images in four levels and four orientation complex wavelet subbands.
2. For each level of the complex wavelet subband
   (a) Extract local phase information of the original and distorted image.
   (b) Compute local phase distortion E_i (where, i is the index for current level) by computing MSE between local phase of the original and distorted image obtained in step (a).
3. Using Equation (2) combine the local phase distortion obtained for each level in step (b) to compute local phase distortion rating in the distorted image.

$$localPhaseDistortionRating = (E_1^{p1}) + (E_2^{p2}) + (E_3^{p3}) + (E_4^{p4}) \quad (2)$$

E_1, E_2, E_3 and E_4 are MSE of local phase coefficients on four frequency levels. $p1$, $p2$, $p3$ and $p4$ are power coefficients and values of power coefficients were 2.1, 2.4, 2.3 and 2.2 respectively.

The Final quality rating of distorted image is computed by using a weighted geometric mean of local magnitude distortion rating and local phase distortion rating, which is shown by equation (3)

$$LMPD = (localmagnitudeDistortionRating)^{\alpha} * (localPhaseDistortionRating)^{(1-\alpha)} \quad (3)$$

Here, the value of α was chosen empirically as 0.6 to generally follow the experimental results. This value gives more importance to local magnitude over local phase.

We also conducted an experiment in which five subjects rated forty-eight phase-distorted images. Twelve original images were used. Each image was phase-distorted with random Gaussian noise in the Level 1, 2, 3, or 4 complex-wavelet subband to create four distorted versions. Subjects were shown twelve original images in twelve rows. In each row, the four phase-distorted versions of the original images were placed. Subjects were instructed to displace the distorted images horizontally such that, each distorted image's horizontal distance from its original image corresponded to the amount of distortion that the subject perceived. Farther the distance, more distorted the image. Subjects were asked to make these judgments of quality related to all other distorted images. The raw distance scores for each subject were converted to z-scores and then averaged across all subjects. Table 1 shows the correlation coefficients (following nonlinear fitting) between the subjective ratings and various quality rating metrics.

Table 1. Correlation coefficient of various quality metrics with subjective ratings

	PSNR	**SSIM[10]**	**CWSSIM[11]**	**NQM[12]**	**VIF[13]**	**MAD[14]**	**LMPD**
Correlation	0.387	0.531	0.458	0.424	0.580	0.281	0.708

4. DISCUSSION

Overall, our results indicate that for the image appearance, the HVS relies on local magnitude more than the local phase, a finding which is consistent with the previous results shown by Shams *et al.*[6] However our results also reveal that local phase can play an equally important role, and in some cases, the local phase can dominate the image's appearance. (It is important to note that the hybrid images created according to the combinations discussed have a major part of the perception which is unrecognizable. The contribution of local magnitude and local phase as a function of spatial frequency reported in this paper is only the contribution of the recognizable part of stimuli.)

4.1 Contribution of low spatial frequency local magnitude

Local magnitude in low spatial frequency not cooperated by local phase and local magnitude in entire spatial frequency range has almost negligible contribution to the image appearance (Combination 1). Even with co-operating local phase (Combination 13) in low spatial frequency the contribution is not substantial (only 26%) as compared to high spatial frequency cooperating information. (By cooperating, we are referring to the case in which the local magnitude and phase come from the same image.) Also when high spatial frequency local magnitude and local phase are not cooperating (Combination 4), low spatial frequency components contribute 44% and rest of the perception i.e 56% come from non-cooperating high spatial frequency content.

4.2 Contribution of low spatial frequency local Phase

Low spatial frequency local phase not cooperated by local phase and local magnitude in entire spatial frequency range, has almost negligible contribution to the image appearance (Combination 1). Similar to low spatial frequency local magnitude, local phase in low spatial frequency has no major contribution in perception when local magnitude and local phase in low spatial frequency are cooperating(Combination 4 and 13).

4.3 Contribution of high spatial frequency local Phase

High spatial frequency local phase not cooperated by local phase and local magnitude in entire spatial frequency range has small contribution to the image appearance (Combination 1, 27% contribution). When local phase in high spatial frequency is in cooperation with low spatial frequency local phase (Combination 3), then local phase in entire spatial frequency range gives 55% of contribution. Even when local magnitude in entire spatial frequency range is cooperating (Combination 12), contribution of local phase does not reduce (contribution of local phase 52%). This suggests that the local phase and local magnitude have equal importance.

4.4 Contribution of high spatial frequency local magnitude

High spatial frequency local magnitude not cooperated by local phase and local magnitude in entire spatial frequency range has the most significant contribution to the image appearance (Combination 1, 59% contribution). When high spatial frequency local magnitude is supported by any other local magnitude or local phase information, then it gives the maximum contribution to the image appearance (Combination 2, 5, 7, 13 and 14).

4.5 What is more important, low or high spatial frequency?

Shulman *et al.*[15] have demonstrated that low and high spatial frequency channels contribute independent information about the image's global and local structure. However researchers studying the effect of spatial frequency on categorization of images have reported that contribution of low and high spatial frequency depends on the task content i.e. the categories that need to be distinguished in low and high spatial frequencies. In between category discrimination uses low spatial frequencies and within category discrimination uses high spatial frequency.[16–19] Oliva *et al.*[20] believe that for between category discrimination middle and high spatial frequencies are used. However, studies mentioned above by other researchers are performed on the global Fourier information of the image. If V1 is dominated by the complex cells which performs local analysis then these studies must be performed locally using complex wavelet or Gabor approximations of complex cells. Also task performed in our experiment was not a categorization task. Task was to measure the contribution of low and high spatial frequencies in image appearance. Results from the experiment have shown that high spatial frequency has the most contribution in the perception of images (Combination 1, 5 and 13).

4.6 What does local phase information implies?

Guyader *et al.*[7] have demonstrated that local magnitude information is sufficient for the recognition task. Also results from Combination 12 have shown that local phase and local magnitude are equally important for the appearance of the images, sometimes local phase dominating local magnitude(Combination 12). Local phase-distortion of images also has a significant effect on image quality. These findings suggest that an explicit mechanism may exist in visual cortex for the computation of local phase information. The neural basis of such a computation however, remains an open question.

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