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Optimizing hybrid images for an easy screening of the visual acuity

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Summary. — The development of a hybrid image (HI) is a method to create a single illusive picture, merging two images with different content in terms of spatial frequencies. Recently such a kind of optical illusion has also been used in the research area of optometry and psychology. Our study is based on the most famous HI, "Einstein-Marilyn face", created in 2007 for the "New Scientist" magazine. This study aims to observe the role of the spatial frequencies in the interpretation of a HI in function of the visual acuity. The results show that a correct selection of the cut-off frequencies is fundamental to generating an optimal HI, *i.e.*, with an optical illusion characterized by a non-ambiguous and stable interpretation. The design of working HIs can open the way for new kinds of tests in the field of optometry, in particular for the screening of myopia.

1. – Introduction

A *hybrid image* (HI) is an optical illusion that consists of merging two different images, creating a single picture whose interpretation changes in the function of the size, viewing distance, and temporal duration. To create such a different interpretation, these two images are altered in their spatial frequency content: one with a lack of high spatial frequency (I_L) and another with a lack at the low ones (I_H). Recently, in addition to entertainment purposes, this kind of optical illusion has also been used in the research area of optometry [1] and psychology [2, 3]. If the two frequency-altered images are suitable to be superimposed, the resulting hybrid image gives the optical illusion [4] of two different interpretations, in a way dependent on the observation condition.

The most famous hybrid image is the "Einstein-Marilyn face", created in 2007 for the *New Scientist* magazine, where the face of the physicist is the I_H, while the actress is

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the I_L [5] (left side of fig. 5). In a close-up vision of the image, Einstein's face strongly prevails and the observer is not able to be aware that an image of a woman's face is hidden in the figure. At a large distance, the high-frequencies components that create Einstein are no longer visible and then the face of Marilyn is revealed and persists till it becomes too blurry to be recognizable.

To create high-quality HIs, a crucial role is played by the cut-off frequencies set in the I_H and in the I_L; in particular, the presence of a frequency gap between the two images is critical to remove the ambiguous interpretation over a large range of distance or size [6-8].

In this study, we have induced the different interpretation effect of the illusion on the observer by introducing a degree of myopia with different lenses, instead of the usual changing of distance and size. Then, here we report a study about the role of the spatial frequencies of an HI in the interpretation in function of the visual acuity of the observer.

The results show that the frequency gap is fundamental to achieving robust stability in interpreting the image for a fixed value of visual acuity. With the term "stability" we mean that there are ranges of distance, size, or visual acuity where different observers experience the same result, with also an impossibility for a conscious or unconscious switching between two different interpretations. Such results can open the way to design new fast pre-screening tests for the detection of myopia.

2. – Images generation

To create the HI, two images (I_1 and I_2) are selected with the same dimension in pixels. Then, the Fourier transforms (F_1 and F_2) of the images are calculated, by the fast Fourier Transform Algorithm (FFT) [9]. In the Fourier domain, the two images are filtered using the convolution theorem, *i.e.*, by multiplication with 2D Gaussian filters (G_1 and G_2) with different widths:

$$F_1^L = G_1 F_1, \qquad F_2^H = (1 - G_2) F_2, \tag{1}$$

where G_1 and $(1 - G_2)$ are the low-pass and the high-pass filter respectively. The cut-off frequency f_L and f_H of each filter are defined as the frequency for which the amplitude drops to 0.5 compared to the original one. The spatial frequencies are here expressed in (cycles/image) [6]. The difference between the cut-off frequencies of the used filters is the gap

$$gap = f_H - f_L. \tag{2}$$

The final two filtered images in the space domain (I_L and I_H) are achieved by the inverse Fourier transform and then superimposed to create the HI:

$$HI = I_L + I_H. \tag{3}$$

Figure 1 shows the scheme of the method (the images of Eistein and Marilyn here processed are the ones also used in a similar work available online [10]).

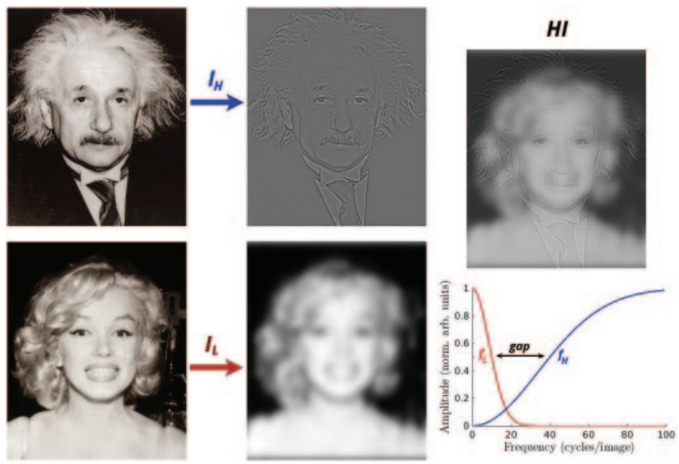

Fig. 1. – Scheme of the image processing to achieve the hybrid image. In the bottom-right, the plot shows the spatial frequency gap between the two used filters.

3. – Data acquisition

The case study is composed of 26 healthy subjects (15 males and 11 females) with ages between 20 and 64 years (the mean and the standard deviation are respectively 30 and 14 years), with a visual acuity (expressed in decimal) of no less than 1.2 on the right eye.

During the preliminary part of the test, the subject under examination is positioned on a chair in front of the CSO's Vision Chart, with the left eye occluded and his usual correction (if needed) on the right. Additional lenses are added or removed to achieve different values of the visual acuity from 1.2 to 0.2 with steps of 0.2, *i.e.*, inducing myopia in the subjects.

In the second part of the measurement, the subject is positioned 2 meters away from support, on which the different hybrid images of the same dimensions are presented. Then, for each value of the visual acuity, the subject should indicate the interpretation of the HI, according to the following possible answers: *Einstein* (I_H), *Marilyn* (I_L), *unstable interpretation* and *impossible interpretation*. The different proposed HIs are generated with different choices of f_H and f_L and also different values of the frequency gap.

4. – Results

The results for all the subjects are collected and three plots (reported in figs. 2–5), each for a different interpretation is created: "Einstein" (blue squares), "Marilyn" (red circles), and "unstable" (black diamonds and dashed line). For each visual acuity, the value of each interpretation is normalized over the total number of answers of the 26 subjects ("Normalized Score"). No markers are reported for the fourth case: "impossible interpretation". Then, if the sum of the score does not reach 1, the meaning is that the image of Marilyn can appear to some observers, so blurry to be no longer recognizable.

Then, three different zones of interpretation can be detected: "*high-frequency zone*" (where the interpretation of I_H prevails and it pertains to high values of visual acuity),

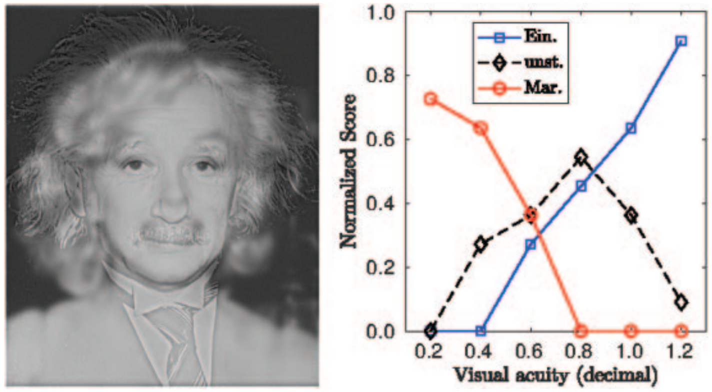

Fig. 2. – HI image with $f_H = f_L = 25$ cycles/image. The unstable zone between the two different stable interpretations appears broad, leading to an ambiguous perception of the HI.

"*instable zone*" and "*low-frequency zone*" (where the interpretation of I_L prevails).

Figure 2 shows a case where the gap between the two cut-frequencies is zero ($f_H = f_L = 25$ cycles/image). As a result, the instability region appears to span over the largest part of the range of the probed visual acuity and then with an unavoidable superposition over the other zone.

In fig. 3, a very different case is presented, where the gap is very large, as well as both the values of the cut-off frequencies ($f_H = 24$ and $f_L = 53$ cycles/image). In particular, the large value of f_H leads to a strong filtering present in I_H, besides a low filtering of I_L, due to the large f_L. Consequently, there is a complete fading of the "*high-frequency zone*".

A better-tuned case is shown in fig. 4, with $f_L = 10$ and $f_H = 40$ cycles/image. The presence of a large gap, besides a value not so small of f_L and not so high of f_H, creates a good compromise that leads to three detectable zones with a small superposition. Hence, as the visual acuity decreases, the interpretation passes from the high-frequency zone to the low-frequency one through a crossover over a small region of instability. The instability zone appears to be detectable only from 0.8 to 0.6 of visual acuity.

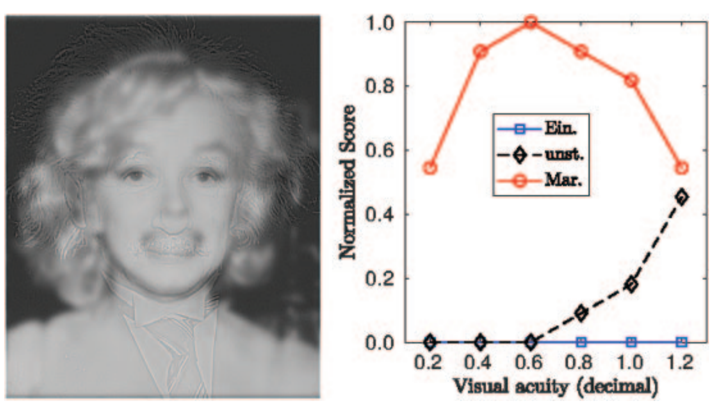

Fig. 3. – HI image with $f_L = 24$ and $f_H = 53$ cycles/image. In this case, the gap is very large (29 cycles/image) and in addition f_H is too high, leading to a fading of a clear perception of the Eistein's face.

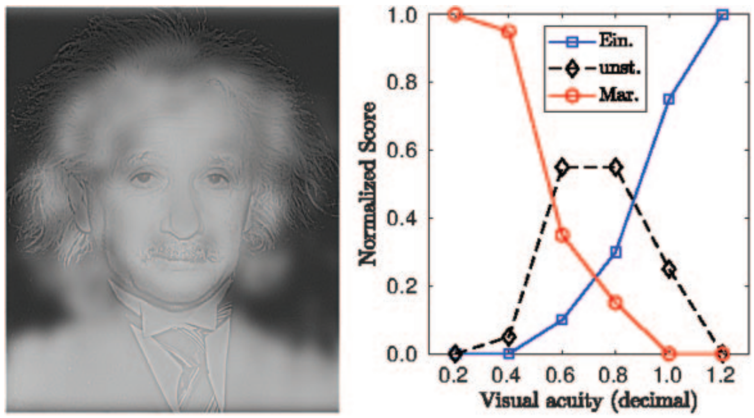

Fig. 4. – A well-tuned values of the cut-off frequencies ($f_L = 10$ and $f_h = 40$ cycles of images. The three regions are clearly detectable, with a reduced superposition.

Other versions of the HI, not reported here, have been studied and their results appear in agreement with the ones presented.

The same experiment was conducted by using the original "Einstein-Marilyn face" of the *New Scientist* magazine (fig. 5). The results show a large high-frequency zone, whereas the range of values of visual acuity with a clear perception of the Marilyn's face is narrow and characterized by subjects that do not perceive to clear image (for visual acuity of 0.2, the normalized score of Marilyn is lower than 0.8). The main important feature of such an original image is the presence of a very weak zone of instability (normalized score less than 0.3). Such a behavior is a good marker for a HI, because the largest part of the observers is able to pass from Eistein to Marilyn without a crossover to a region characterized by an ambiguous or switchable interpretation.

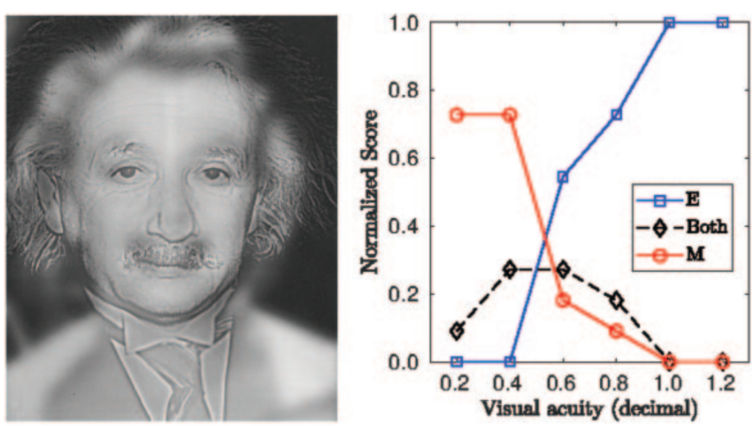

Fig. 5. – The original "Einstein-Marilyn face", created for the *New Scientist*. The weakness of the instability zone, *i.e.*, the region of ambiguous or switchable interpretation, is the main feature of this hybrid image.

5. – Discussion and conclusion

In this study, we have reported how the development of the hybrid images can be tuned to create a well-working hybrid image. Such optical illusions are generated by superimposing two different figures, one filtered respectively with a low pass filter and the other with a high pass filter, in terms of spatial frequencies.

The results suggest which is an optimal "recipe" to obtain the best image and then reduce the instability zone: the gap between the two filtered frequencies, paying attention to not choosing cut-off frequencies that could inhibit an interpretation expected for a given visual acuity. Concerning the original "New Scientist"- version, the main feature that underlines its high quality is the weakness of the instability zone.

In conclusion, we have reported that the use of such a kind of optical illusion, taking into account the prescriptions here underlined in terms of the choice of cut-off frequencies, can also be promising and useful in the field of Optometry. In particular, HI, with stable interpretation, can be a candidate for a new, fast, and simple screening for myopia, because the interpretation of the image can be used as a probe of the visual acuity.

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