What is a visual stimulus?

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ABSTRACT

When two stimuli, s_1 and s_2 , having different phase spectra are added we get not only that the amplitudes in $(s_1 + s_2)$ will be reduced relative to the amplitudes in s_1 plus the amplitudes in s_2 but also that the distribution of amplitudes in the spectra (as well as the spectrum of the squares of the amplitudes) may be altered. Yet their appearance may remain unaltered. When the amplitude spectrum of a stimulus has been altered it can no longer be held to be the same stimulus. Visual stimuli can, therefore, not be counted on to be the same stimuli when they are combined as when they are presented in isolation even if they have the same appearance. This is due to interference in the stimuli which is unrelated to vision. These observations, it would seem, have implications for a number of areas in visual science among them visual masking, visual crowding, visual search, and for the adding of noise to stimuli.

Key words: Appearance; Fourier Transform; interference; amplitude; phase; crowding; masking; visual noise.

One often encounters descriptions of visual stimuli in terms of their appearance. This raises the question: Can visual stimuli be defined in terms of how they appear? [FOOTNOTE 1] That a stimulus can be different from its appearance is recognized in connection with visual illusions in which the illusion consists precisely in a discrepancy between the appearance of the stimulus and its physical characteristics. In the present short note I point out another, and perhaps less obvious, reason for why a stimulus cannot be equated with its appearance.

Let us consider a very simple 1-dimensional signal consisting of 8 elements out of which all except for two have been set to zero. The two elements not set to zero have been given the value of 1. These two non-zero values occupy positions 2 and 3 in the signal. This signal is depicted in Fig. 1A. (One could think of this as a cross-section through a 2-dimensional visual stimulus.) In Fig. 1B is shown the same signal with the order reversed. In Fig. 1C is shown the two signals added (i.e., $\text{Fig. 1C} = \text{Fig. 1A} + \text{Fig. 1B}$).

Fig. 1. (A) A 1-dimensional signal of 8 elements with all values set to 0.0 except for the values in positions 2 and 3 which have been set to 1.0. (B) The same signal as in A but with the order reversed. (C) The sum of the signals in Panel A and in Panel B.

In Fig. 2 is shown with dashed line the amplitude spectrum of the signal in Fig. 1A plus the amplitude

spectrum of the signal in Fig. 1B. The two signals have identical amplitude spectra (amplitude spectra are translation invariant and Fig. 1B is a translation of Fig. 1A) so the spectrum of each signal is half that shown here. The solid line in Fig. 2 shows the amplitude spectrum of the combined signal (i.e., of Fig. 1C). At several frequencies the amplitude spectrum of this signal falls well below the amplitudes for the two signals determined separately and then added (i.e., the dashed line). For components 1, 3, 5 and 7 there are zero amplitudes in the spectrum of the combined signal (solid line) whereas the individual signals (dashed line) have substantial amplitudes at all of these frequencies. Thus, combining the signals causes a fundamental re-shaping of the spectrum.

Fig. 2. Dashed line shows the amplitude spectrum of the signal in Fig. 1A plus the amplitude spectrum of the signal in Fig. 1B when the two spectra are determined separately. The solid line shows the amplitude spectrum of the signals in Fig. 1A and Fig.1B combined. That is, it shows the amplitude spectrum of the signal in Fig. 1C. Notice that the amplitude spectrum of the combined signal (solid line) is not merely a scaled down version of the individual spectra (dashed line) but represents a fundamental re-distribution of the amplitudes.

The sum of amplitudes in both Fig. 1A and Fig. 1B is 3.55. That is, the sum of amplitudes in the two signals determined separately and then added is 7.10. On the other hand, the sum of amplitudes in the two signals combined in Fig. 1C is only 3.41. Thus, the sum of amplitudes in the signal in Fig. 1C is only 0.48 of the sum of amplitudes in the signal in Fig. 1A plus the sum of amplitudes in the signal in Fig. 1B. The reduction in amplitudes in the combined signal is due to interference between the two signals. (For a brief

explanation of how interference may reduce the amplitudes when signals are combined see the *Appendix*, or see Skottun, 2018a, b, c: 2020, for more extensive explanations.) Thus, the full sum of amplitudes of the signal in Fig. 1A and the sum of amplitudes of the signal in Fig. 1B cannot both be contained in the

Fig. 3. Amplitude squared (i.e., power) as a function of frequency. Solid line shows the values for the combined stimulus (i.e., Fig. 1C) and the dashed line shows the results for the individual stimuli, i.e., for Fig. 1A plus Fig. 1B. For the individual stimuli (dashed line) the amplitudes were squared before they were summed. Thus, while the values represented by the solid line are the squares of the ones represented by solid line in Fig. 2, the values represented by the dashed line are not the direct squares of the values represented by dashed line in Fig. 2.

amplitudes of the combined signal (i.e., in the amplitudes of the signal in Fig. 1C). We thus have both that the distributions of amplitudes in the spectra are altered (Fig. 2) and that the amount of amplitudes are severely reduced when the signals are combined. If the two signals do not have the same amplitudes and not the same amplitude spectra after they have been combined one cannot maintain that they remain *the same signals*.

These considerations have been based on the amplitudes, were one to sum the square of the amplitudes, i.e. the power, one may get that the sum of the squared amplitudes in the combined signal is equal to the sum of the squared amplitudes in the two individual signals (i.e., that $\sum (A + B)^2 = \sum A^2 + \sum B^2$, where A and B represent the amplitude spectra of two different signals). This may perhaps lead some to conclude that the combination of two signals equals the sum of the two signals. That this can not be counted on to

Fig. 4

Fig. 4. (A) A visual stimulus which has the appearance of a horizontal white rectangle on a black background. (B) The same stimulus as shown in Panel A except that the rectangle has been translated vertically downwards. (C) The stimuli in Panels A and B added together.

be the case is demonstrated in Fig. 3 in which are shown the squared amplitudes (i.e., power) as a function of frequency. Again, as was the case for amplitudes (i.e., Fig. 2) the spectrum of the combined signal (solid line) is fundamentally different from the spectra of the individual signals when these are calculated and then added (dashed line). And, as was pointed out in connection with amplitudes, when the spectra are different one cannot speak of the same signal. This ought to serve as a warning that were one to focus on the sum of the squared amplitudes (i.e., on the power) one may fail to realize that the two signals added may be (and most commonly are) different from the sum of the two signals considered separately.

The 1-dimensional signals in Fig. 1 may seem unrepresentative of actual visual stimuli which typically vary along two spatial dimensions. A part of the analysis was therefore repeated with what may be considered more realistic visual stimuli. In Fig. 4A is shown a white rectangle on a black background. The rectangle has the dimensions of 32 x 8 elements. and the whole image has the dimensions of 64 x 64 elements. The rectangle, which appears white, has a value of 1.0 whereas the background, which appears black, has a value of 0.0. By taking the amplitudes of the Fourier Transform of this stimulus we get a value of 284.32 for the sum of all amplitudes.

Figure 4B shows the same rectangle but translated (shifted) downwards. Since this figure contains the same rectangle it has the same amplitudes (again, amplitude spectra are invariant under translation). Consequently, it also has a sum of amplitudes of 284.32. Thus, together the stimuli in Panels A and B have a total sum of amplitudes of 568.64.

In Fig. 4C is shown the two stimuli added (i.e., Fig. 4C = Fig. 4A + Fig. 4B). By computing the amplitudes of the Fourier Transform we get that the stimulus in Fig. 3C has a total sum of amplitudes of 339.48. This is substantially less than the sum of amplitudes of 568.64 in the two stimuli determined separately and then added. In fact, it is about 60 % of the sum of amplitudes in Fig. 4A plus the sum of amplitudes in Fig. 4B (to be precise, it is 59.7 % of the sum of the two stimuli determined separately). If we denote the Fourier Transforms of the stimuli in Figs. 4A and 4B by F_A and F_B , respectively, and the amplitude operator by $|\cdot|$ we have that $\sum |F_A + F_B| < \sum |F_A| + \sum |F_B|$. In other words, the amplitudes of the sum is smaller than the sum of the amplitudes.

As was the case in Fig. 1 above the reduction is due to interference between the two stimulus elements.

Interference takes place between the stimulus elements *in the stimuli* and does not depend on them being seen. It is unrelated to vision.

It seems quite clear that when the sum of the amplitudes in the two stimuli determined separately is 568.64 and the amplitudes in the combined stimulus is only 339.48 the full amplitudes of both stimuli cannot both be contained in the combined stimulus (i.e., in Fig. 4C). In the present case the two stimuli are identical (except for vertical translation which does not affect amplitudes) we can therefore assume that the amplitudes in both stimuli are reduced equally. That is to say, in the combined stimulus the amplitudes of each rectangle are reduced to about 60 % of the magnitudes they had when they were presented separately (as in Fig. 4A and 4B). It is also clear that the upper rectangle in Fig. 4C is the same as the one in Fig. 3A and that the lower rectangle in Fig. 4C is the same as the one in Fig. 4B. Thus, the upper rectangle in Fig. 4C has the same appearance as the one in Fig. 4A. Likewise, since the lower rectangle in Fig. 4C is the same rectangle as the one in Fig. 4B it has the same appearance. But, if the amplitudes are different (such as being reduced by about 40 %) in the combined stimulus we cannot maintain that they are the same stimuli. The paradox becomes, therefore, that while we are justified in saying that the upper rectangle in Fig. 4C is the same *rectangle* (or the same *figure*, or the same *shape*) as the one in Fig. 4A and that the lower *rectangle* in Fig. 4C is the same as the one in Fig. 4B we may not say they are the same *stimuli*.

The fact that the appearances may be the same while the stimuli are different due to them having different amplitude spectra suggests a similarity with metamerism color stimuli: "... metamerism color stimuli are color stimuli that have different spectral radiant power distributions but match in color for a given observer" (Wyszecki & Stiles, 2000. p. 185). In other words, they are colors which are seen as being the same but which have different physical compositions. We should like to say they are the same *color* but different *stimuli*.

In conclusion, when a stimulus (or stimulus element) is presented along with other stimuli (or with other stimulus elements) one cannot count on it being the same stimulus (or same stimulus element) as when it is presented in isolation. These considerations apply to most, if not all, all instances where visual stimuli are being combined. For instance, a target stimulus presented on top of visual noise cannot be counted on to be the same stimulus as when presented without noise (Skottun, 2021). And, in the case of visual search a target stimulus cannot be counted on to be the same stimulus when presented in isolation as when presented in a field of distractors (Skottun, 2018e). Likewise, in visual crowding and masking a target stimulus cannot be assumed to be the same when presented along with flanking or masking stimuli as when it is presented

by itself (Skottun, 2018b, 2020).

METHODS

Numerical analyses were carried out using *Mathematica* (Wolfram Research) and *GNU Octave*.

FOOTNOTE

1. Some may perhaps argue that this would be a confusion of the stimulus and the response as the appearance may more appropriately be linked to the response to the visual stimulus than to the stimulus.

APPENDIX — A FEW REMARKS ON INTERFERENCE

As for why the elements presented together have different and/or less amplitudes than the amplitudes of the elements in isolation the short answer is: Because the two elements differ in spatial phase. For a fuller answer consider the following: The Fourier Transform transforms signals into series of sine functions. The amplitude of a sine function (i.e., of a Fourier component) can be written as $a = |a e^{i\omega(x-\phi)}|$ where $|\cdot|$ is the amplitude operator, a is a constant denoting the amplitude, $i = \sqrt{-1}$, ω denotes the frequency, x is the position, and ϕ gives the phase. The amplitude of this function equals a for all frequencies, phases and values of x . Thus, when adding the amplitudes of two sine functions of the same frequency we get $a_1 + a_2 = |a_1 e^{i\omega(x-\phi_1)}| + |a_2 e^{i\omega(x-\phi_2)}|$. This holds irrespective of any difference in spatial phase. But this holds only when amplitudes are first determined and then added. However, when we add two sine functions and *then* compute the amplitude we get $|a_1 e^{i\omega(x-\phi_1)} + a_2 e^{i\omega(x-\phi_2)}| < a_1 + a_2$ when $\phi_1 \neq \phi_2$. In this case we have that the amplitude depends on the relative phase of the two functions. That is, when the phases differ the amplitude of the sum is smaller than the sum of the amplitudes. To see this, consider the case where a sine function is added to another sine function which is 180 degrees (π radians) out of phase. In this case the two functions annihilate each other and we have an amplitude for the sum of the two functions of 0.0 (see, e.g., Fig. 1 of Skottun, 2018a). This is referred to as interference. (For further discussions and background material see Skottun, 2018a, b, c; 2020). There may also take place interference between stimuli which are separated in time (such as, e.g., between two alternating stimuli). What is required is that the different stimuli fall within the time window within which stimulation is integrated. In such cases there may be interference both across time and space requiring analyses based on 3-dimensional (X,Y,t) Fourier Transforms (Skottun, 2018d).

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