Interference in Tilt-Illusion stimuli: A simple illustration

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ABSTRACT

The relevance of relative phase for addition of amplitude spectra was demonstrated by comparing the effect of three phase differences, 0, $\pi/2 = 90$ degrees, and $\pi = 180$ degrees, with two theoretical amplitude spectra displaced relative to each other as they would if they represented stimuli of different orientations. Differences in phase cause the amplitudes in the combined stimulus to be reduced relative to the sum of amplitudes in the two spectra. Because the reductions are most pronounced where the spectra overlap, in the case of partially overlapping spectra this may cause the two spectra to be effectively shifted away from each other. In the case where the spectra belong to stimuli of different orientations such shifts may cause the apparent angle between two stimuli to increase. This may be consistent with the Tilt Illusion. In which case it may be possible to account for this illusion based on the stimuli without implicating the visual system.

Key words: Amplitudes; Fourier; Tilt After Effect; orientation; Zollner Illusion; Hering Illusion.

INTRODUCTION

When an elongated stimulus is presented along with another elongated stimulus having a somewhat different orientation the angle between them may appear larger than it actually is (Gibson, 1937; Gibson & Radner, 1937; Westheimer, 1970; Over et al., 1972; Carpenter & Blakemore, 1973; Georgeson, 1973; Schwartz, et al., 2007, 2009; Kaneko et al., 2017). This phenomenon is known as the "Tilt Illusion" (Clifford, 2014). The Tilt Illusion has generally been attributed to interactions in the visual system (Blakemore et al., 1970, 1973; Wenderoth & Johnstone, 1987; Clifford et al., 2000; Series et al., 2003; Solomon & Morgan, 2006; Clifford, 2014; Song & Rees, 2018; Steinwurz et al., 2020; Takao et al., 2020). However, it has become clear that there may be interference in the kinds of stimuli employed to elicit this illusion (Skottun, 2018d). Such interference may cause the amplitude spectra of the two stimuli to be "pushed away" from each other. The interference may have the effect of making the angle between the stimuli appear larger than it is. This may be consistent with the Tilt Illusion and opens for the possibility of accounting for this illusion based on the stimuli without having to invoke the visual system. An account in terms of interference would be very parsimonious since it would require no "mechanisms" (i.e., no neuronal substrate and no involvement of vision or the visual system) because interference is a simple and inevitable consequence of the addition of signals. That interference has the ability to alter the appearance of orientation in visual stimuli has been indicated previously (Skottun, 2018d). The procedure followed in that report may be difficult to follow. The goal of the present report is to attempt to provide a simpler and more intuitive illustration of how interference may alter the appearance of orientation in visual stimuli.

ANALYSES

Interference can be most easily understood in terms of Fourier components. Each component in a Fourier spectrum consists of a complex number which may be represented by a vector in the complex plane (Fig. 1). The length of this vector gives the amplitude and its direction represents the phase angle. When two Fourier components are added we have, therefore, the addition of two vectors. When the two vectors differ in direction the length of the vector representing the sum will be smaller than the sum of the lengths of the two vectors when these are determined separately (Fig. 1A; see also Skottun, 2018a, and Skottun, 2018c). This is known as the "triangle inequality". Thus, we have that the amplitude of the sum is smaller than the sum of amplitudes when the phases differ. If we denote the amplitude operator with $|\cdot|$ and let a and b represent two Fourier components we have $|a + b| < |a| + |b|$ when the phases differ. (The amplitude of a

Fourier component, z , is defined as $|z| = \sqrt{Re(z)^2 + Im(z)^2}$, where $Re(z)$ and $Im(z)$ return the real values of the real and imaginary parts of z , respectively.)[FOOTNOTE 1]

Fig. 1

Fig. 1. (A) A sine wave function having zero phase (i.e., $\sin(x)$)(solid line), a sine wave function having a phase $= \pi/3 = 60$ degrees (i.e., $\sin(x - \pi/3)$)(dashed line), and the sum of the two (i.e., $\sin(x) + \sin(x - \pi/3)$)(dotted line). Note that the amplitude of the sum is smaller than the sum of the amplitudes (i.e., that $|\sin(x) + \sin(x - \pi/3)| < |\sin(x)| + |\sin(x - \pi/3)|$) (B) The same summation carried out as vector addition. As can be seen, the length of the vector representing $\sin(x) + \sin(x - \pi/3)$ is smaller than the length of the vector representing $\sin(x)$ plus the length of the vector representing $\sin(x - \pi/3)$. These examples illustrate that the transform of a signal into its amplitude spectrum is a non-linear transformation.

In the case where there is no difference in phase (i.e., no difference in direction of the vectors) the amplitude of the sum is equal to the sum of the amplitudes (Fig. 2A). However, were we to assume that the two components differed in phase by $\pi/2$, i.e. by 90 degrees, we would have to add them as the diagonal in a right-angle triangle with the sum now becoming $|a + b| = \sqrt{|a|^2 + |b|^2}$. This is illustrated in Fig. 2B.

In the case where components differ in phase by $\pi = 180$ degrees (i.e., vectors having opposite directions) we get $|a + b| = ||a| - |b||$. (Please note that this strange equation only holds when the vectors have opposite directions.) This is illustrated in Fig. 2C. (Since the difference between two amplitudes can be negative while amplitudes cannot have a negative value it is important to take the absolute of the difference.)

Let us define two gaussian distributions $a(\omega) = e^{-(\omega-c)^2/(2\sigma^2)}$ and $b(\omega) = e^{-(\omega+c)^2/(2\sigma^2)}$ that are identical except for being translated (shifted horizontally) relative to each other by $2c$, where c is a real number (Fig. 3A). We now assume that these two functions denote amplitude spectra with ω denoting frequency. (Thus we have that $a(\omega) = |a(\omega)|$ and $b(\omega) = |b(\omega)|$.) Were we to add these two amplitude spectra by assuming zero difference in phase we would have that $|a(\omega) + b(\omega)| = |a(\omega)| + |b(\omega)|$. That is, the amplitude of the sum is equal to the sum of the amplitudes. The sum of the two spectra in Fig. 3A summed in this manner

is shown with a solid line in Fig. 3B.

Fig. 2

Fig. 2. Adding two Fourier components. (A) The summing of two components when there is no difference in phase. In this case the amplitude of the sum equals the sum of the amplitudes. That is, $|a + b| = |a| + |b|$, where $|a|$ and $|b|$ give the amplitudes of the components a and b . (B) When the phase difference between the components is $\pi/2 = 90$ degrees the sum of the amplitudes becomes the diagonal in a right-angled triangle and the sum of two components, a and b , will be given by $|a + b| = \sqrt{|a|^2 + |b|^2}$. (C) When the phase difference is $\pi = 180$ degrees the sum of two components becomes the absolute of their difference. Thus we get what may seem paradoxical: $|a + b| = ||a| - |b||$. Since the difference between two amplitudes may attain a negative value if $|b| > |a|$ one needs to take the absolute of the difference as amplitudes cannot be negative. (A negative amplitude is actually a positive amplitude but with a phase change of $\pi = 180$ degrees.)

However, in the case where the two spectra differ in phase by $\pi/2$, i.e. by 90 degrees, we would have to add them as the diagonal in a right-angle triangle (as shown in Fig. 2B) with the sum now becoming $|a(\omega) + b(\omega)| = \sqrt{|a(\omega)|^2 + |b(\omega)|^2}$. The result of such summation is shown with a dashed line in Fig. 3B. Further, if the spectra were to differ in phase by $\pi = 180$ degrees we have to write $|a(\omega) + b(\omega)| = ||a(\omega)| - |b(\omega)||$ (as illustrated in Fig. 2C). The result of adding the two spectra in Fig. 3A in this way is shown with a dotted line in Fig. 3B. (For further emphasis is shown in Fig. 3C the amplitude after summation relative to the sum of amplitudes prior to summation, i.e., $|a(\omega) + b(\omega)| / (|a(\omega)| + |b(\omega)|)$, for

phase differences of 0, $\pi/2$, and π .)

Fig. 3

Fig. 3. Adding two theoretical 1-D amplitude spectra, $a(\omega)$ and $b(\omega)$, which are identical with the exception that they have been shifted (translated) relative to each other along the ω -axis (ω denotes frequency).

(A) The two amplitude spectra. (B) The sum of the two spectra added with a phase difference between them of zero degrees (solid line), added with a phase difference of $\pi/2 = 90$ degrees (dashed line), and added with a phase difference of $\pi = 180$ degrees (dotted line). (C) The relative amplitude as a function of ω for when the phase difference is 0 degrees (solid line), when it is $\pi/2 = 90$ degrees (dashed line) and when it is $\pi = 180$ degrees (dotted line). The relative amplitude is given by $|a(\omega) + b(\omega)|/(|a(\omega)| + |b(\omega)|)$. It can be understood as the the sums of the functions when the phase difference is 90 and 180 degrees relative to when it is 0 degrees.

As can be seen from Fig. 3B, when the two functions are added with a phase difference unequal to zero

Fig. 4

Fig. 4. (A) A Gabor function with a carrier grating tilted 10 degrees counter-clockwise. (B-D) A Gabor function with a carrier tilted 10 degrees clockwise. Panels B, C, and D show functions with carriers of 0, $\pi/2$, and π phase difference relative to the one in Panel A, respectively.

we have that the amplitudes are reduced in the region where the functions overlap. In our example this is the region between the peaks of the two functions. The reductions are larger for a phase difference of π than for a difference of $\pi/2$. These reductions cause the bulk of the amplitudes of $a(\omega)$ and $b(\omega)$ to be shifted away from each other.

For instance, the *expectation value* of ω for $a(\omega)$ and $b(\omega)$ will be shifted away from each other. For a function $f(x)$ the *expectation value* is given as $\langle f(x) \rangle = \int x f(x) dx / \int f(x) dx$. (This, it should be noted, is different from the *average value* which is given by $\int_a^b f(x) dx / (b - a)$.) For $a(\omega)$ with $c = 30$ elements and $\sigma = 20$ elements the *expectation value* will, of course, be 30 elements. In the case of this function after it has been added to $b(\omega)$ (also having $c = 30$ elements and $\sigma = 20$ elements) and assuming a phase difference of π (i.e. 180 degrees) the *expectation value* becomes 34.6 elements, which entails a shift of 4.6 elements. Since $b(\omega)$ is shifted by an equal amount in the opposite direction we have that the distributions have been shifted away from each other by $2 \times 4.6 = 9.2$ elements.

The above analyses were carried out with theoretical amplitude spectra. To show that shifting of amplitude spectra may occur with actual stimuli the analyses were also carried out with amplitude spectra derived from actual stimuli. Figure 4 shows two Gabor functions, one with a carrier grating tilted 10 degrees counterclockwise (Fig. 4A). The other function (Fig. 4B-D) had a carrier grating tilted 10 clockwise making the difference in orientation 20 degrees. The Panels B, C and D show the same function with the only difference being in regard to spatial phase. The Gabor function in Fig. 3A has phase angle of 0. The three Gabor functions in Fig. 4B, 4C, and 4D have phase angles of 0, $\pi/2 = 90$ degrees, and $\pi = 180$ degrees, respectively. (The phase angles refer only to the carrier grating. The position of the Gaussian envelope remained unaltered.)

In Fig. 5A is shown the 2-D amplitude spectrum of the function in Fig. 4A plus the one in Fig. 4B. In Fig. 5B are shown cross sections through the amplitude spectra along the vertical line in Fig. 5A. Solid, dashed and dotted lines show cross sections for when the two stimuli differ in phase by 0, $\pi/2$, and π , respectively. (I.e., for when adding Fig. 4A and Fig. 4B, adding Fig. 4A and Fig. 4C, and for adding Fig. 4A and Fig. 4D, respectively.) As ought to be apparent, these results match quite closely those for the theoretical 1-D functions shown in Fig. 3B. Again, we see that when there are phase differences the amplitudes in the region between the peaks of the functions are reduced causing the two amplitude spectra to be "pushed apart".

Fig. 5

Fig. 5. (A) Amplitude spectrum of the combination of the Stimulus in Fig. 4A and the one in Fig. 4B. Brighter areas denote larger amplitudes. (B) Amplitude as a function of position along the vertical line in Panel A. Solid, dashed and dotted lines give amplitudes for phase differences of 0, $\pi/2$ and π , respectively.

DISCUSSION

Above has been shown the addition of two theoretical 1-D (Fig. 3) and two actual 2-D (Fig. 4 and Fig. 5) amplitude spectra. The spectra have been added for three different phase differences: 0, $\pi/2$, and π . As ought to be apparent from the figures, interference due to phase differences of $\pi/2$ and particularly π can result in pronounced reductions in the amplitudes in parts of the combined spectra.

It should be emphasized that interference is an inevitable consequence of the adding of signals. It requires no "mechanisms", no neurophysiology, or no visual system. Nor does it require that the signals are being seen. That is, interference takes place whether the stimuli are seen or not. All that is required is that stimuli are added. It offers, therefore, a very parsimonious account.

In the cases where interference is present it will be most pronounced in the region with the greatest overlap. In the present examples the two Gaussian amplitude spectra were generated so as to be translated (shifted) relative to each other which made the reductions most pronounced in the region between the peaks. In the case where the amplitude spectra are those of two differently oriented elongated stimuli this may cause

the bulk of the amplitudes to become shifted away from each other causing the apparent angle between the space domain stimuli to be increased (Skottun, 2018d). In this way interference may not only reduce the stimulus power (i.e., not only reduce amplitudes when stimuli are combined, Skottun, 2018a, b, c) but may alter the appearance in visual stimuli in other ways (Skottun, 2018d, 2019). As has been shown previously (Skottun, 2018d), such shifts may be consistent with the Tilt Illusion. [FOOTNOTE 2] These observations may also have implications for the understanding of the Hering Illusion and the Zollner Illusion (Skottun, 2019).

In the case of pairs of actual stimuli there will typically be a range of phase angle differences and different components will typically differ by different amounts. For the sake of exposition it has here been assumed that all components differ by the same amount and only three particular phase differences (0 , $\pi/2$, and π) were examined. These simplifying assumptions were made in order to better illustrate the importance of differences in phase. It is only when the Fourier spectra have zero difference in phase that the amplitude spectrum of the sum equals the sum of the two amplitude spectra. That the difference in phase angles between the spectra of two different stimuli is zero happens rarely [FOOTNOTE 3]. Thus, for all practical purposes phase angles need to be taken into account when considering responses to the sum of two (or more) visual stimuli. As a consequence, not only can a stimulus not be counted on to have the same stimulus power when presented in combination with other stimuli as when presented by itself (Skottun, 2018a, b c) it can also not be counted on to have the same appearance (Skottun, 2018d, 2019).

The above analyses have dealt only with the stimuli. That is, the visual system has played no role. In this connection two issues need to be addressed.

Dichoptic viewing. The Tilt Illusion can be obtained with dichoptic viewing (Paradiso et al., 1989; Wade, 1980; Forte & Clifford, 2005). That is, it can be obtained with one stimulus presented to one eye and the other stimulus to the other. In this case, obviously, the visual system has to be involved in combining the stimuli. However, if we assume that binocular summation is summation. That is, if we assume that the stimuli from the two eyes are added, interference would still be possible. In other words, the induced tilt could still be accounted on based on the stimuli. As far as interference is concerned it makes no difference where the addition takes place. Addition is addition!

Tilt After Effect. We have here focused on the kinds of interactions which can result in the Tilt Illusion when the two stimuli are presented at the same time. A related phenomenon is the Tilt After Effect (Gibson &

Radner, 1937; Campbell & Maffei, 1971; Paradiso et al., 1989). In this after effect viewing of one elongated adapting stimulus induces illusory shift in the apparent orientation of a subsequently presented elongated target stimulus. The Tilt Illusion and the Tilt After Effect seem to share some characteristics. This leads to the question of if, or to what extent, interference may play a role in the Tilt After Effect. It seems quite clear that there may be interference between stimuli along the time dimension (Skottun 2018e). How this may affect the Tilt Illusion if the two stimuli are presented at two different times is not yet clear. What is required is that the stimuli fall within the temporal window inside of which stimulation is being summed. There is evidence to indicate that full summation may extend to about 100 ms whereas partial summation can extend to as much as 1000 ms (Legge, 1978). In addition to interference along the time dimension due to the relatively long temporal integration window (as just described) there may be spatial interference between stimuli presented at somewhat different times. Whether or not the temporal integration window is large enough to account for interference in the Tilt After Effect is unclear. The fact that the presentation of the adapting stimulus influences the appearance of the subsequently presented target stimulus entails that some physiological event has sufficiently long integration time to cause the after effect. In order to be able to exclude a role of interference in the Tilt After Effect one would have to be able to show that inter stimulus interval in the Tilt After Effect is too long for interference to take place. That is, one has to show that the temporal integration (of whatever neuronal entities are involved) is long enough to account for Tilt After Effect but is unable to subserve interference over this duration. What ought to be clear however is that interference needs to be taken into consideration when the Inter Stimulus Intervals between the adapting stimulus and the target stimulus is short.

The present illustrations ought to make it clear that in order to understand the responses to visual stimuli one must first understand the stimuli [FOOTNOTE 4]. In connection with how one may be deceived by the senses St. Augustine wrote more than 1500 years ago (in *Contra Academicos*, 2.11.26, English translation 1995) of how an oar appears bent when stuck in water. This may be called a visual illusion. For this he wrote of a "cause intervening so that the oar should appear bent." And he went on: "If it were to appear straight while dipped in the water, then with good reason I would blame my eyes for giving a false report." The "intervening cause" is, of course, the refraction of light rays in the air-water interface. Clearly, he did not attribute the illusion to "his eyes". Rather, it would seem St. Augustine attributed this illusion to what we would now call "the stimuli". Can we say the same of the Tilt Illusion?

FOOTNOTES

1. It is important to distinguish between Fourier spectra and amplitude spectra. The transform of a signal into its Fourier spectrum is linear and one-to-one. The transform of a signal into its amplitude spectrum is neither (except when all the phase angles are zero). The Fourier spectrum of the sum of two signals is equal to the sum of their Fourier spectra. The same holds for amplitude spectra only when the phase spectra of the two signals are identical.

2. The amount of induced tilt in the Tilt Illusion depends on the angle between the two stimuli (see, e.g., Fig. 1B of Clifford 2014). Some authors have found in addition to the main effect of an increase in apparent angle a small inverse Tilt Illusion at large differences in orientation between the stimuli (at above about 50 degrees difference in orientation). (Again see Fig. 1B of Clifford 2014 for an example.) This is at odds with what is to be expected based on interference (see Fig. 3a of Skottun, 2018d). It is not clear what significance is to be attached to this since several authors have found little or no evidence for such an inverse effect in actual experiments (Carpenter & Blakemore, 1973, see their Fig. 7; Over et al. 1972, their Fig. 1; Virsu & Tarskinen, 1975, their Fig. 5; Walker, 19978, his Fig. 3).

3. In the present demonstrations two Gabor functions with zero phase difference were employed (i.e., Fig. 4A and Fig. 4B). This is possible in theoretical analyses such as the ones carried out here. However, in practice this would require that the stimuli be superimposed. In such a case one would, most likely, not be able to determine the orientations of each of the Gabor functions. In the case of two differently tilted lines these will tend to differ in spatial phase. It may be proposed that one could make two stimuli have the same phase spectra. The problem with this approach is that since the appearance of images is substantially determined by their phase spectra (Oppenheim & Lim, 1981; Piotrowski & Campbell, 1982) the stimuli will then become very similar and would not be representative of those typically employed to generate the Tilt Illusion.

4. For an example of how what was once considered a problem became near obvious once the stimuli were understood see Skottun et al. (1994).

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