Interference in visual search stimuli

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ABSTRACT

In tests of visual search it is found that the response time increases with set size under some stimulus conditions whereas it may be relatively independent of set size under other conditions. The present study investigates interference in the kinds of stimuli employed in such experiments. Interference takes place in the stimuli and does not depend on the visual system or on attention. Two scenarios were explored:

(1) Interference between all elements, and (2) interference between a target and a single background made up of a set of elements. In the former case interference increases monotonically with set size. In the latter case there is a mild amount of interference which remains relatively independent of set size. By assuming the response time increases with the inverse of stimulus power (response time $\propto 1/(1 - \text{interference})$) it is found that when there is interference between all the elements the simulated response time increases monotonically with set size. On the other hand, when the interference is between a target and a single background the simulated response time remains largely unaffected by set size.

Key words: Stimulus power; set size; attention; serial; preattentive; distractor.

INTRODUCTION

It has become clear that there may take place interference between visual stimuli or between separate elements in visual stimuli (Skottun, 2017a, 2017b, 2018). As is explained below, such interference causes the total amount of amplitudes in the stimuli when taken together to be smaller than the sum of the amplitudes in the stimuli when these are determined separately. In other words, interference causes the amplitude of the sum to be smaller than the sum of the amplitudes. When this occurs the full amplitudes in all the stimuli cannot all be contained in the amplitudes of the combined stimulus. [FOOTNOTE 1]

Interference has been studied in relation to stimulus configurations in which there is one target stimulus and one masking stimulus or where there is one target stimulus and one masking stimulus which, even though it may consist of several elements, is being treated as one stimulus (Skottun, 2017a, 2017b). Thus, the interference has been estimated as it may exist between only two entities. For instance, interference has been examined as it may take place between a target stimulus and a set of masking stimuli or between a target stimulus and set of flanking stimuli in which the masking or flanking stimuli have been taken together as a single entity.

In certain kinds of visual tasks a subject is required to identify a target stimulus embedded in a field of distractor elements. It is then sometimes found that the response time increases monotonically with the number of elements in the display. This has been taken as evidence for serial search. In other words, it has been interpreted as evidence for attention being shifted sequentially across the field of elements. (Treisman & Gelade, 1980; Wolfe et al., 1992). On the other hand, with other stimuli the response time is unaffected by set size. Such performance has been characterized as "preattentive". Before drawing conclusions regarding the presence versus absence of attention it would seem one ought to investigate the effect upon the stimuli of adding elements. That is to say, one ought to determine what effect this may have upon the stimuli as these exist independently of vision and attention.

It would seem that the results from experiments on visual search have been interpreted with the tacit assumption that the stimulus elements have the same stimulus power when they are presented together as when they are presented in isolation. In other words, it appears to have been assumed that increasing the number stimulus elements in a display does not alter the stimulus power of the individual elements and, consequently, that a target stimulus has the same stimulus power when is it presented with few distractors as when presented with many distractors. [FOOTNOTE 2] The present report examines this assumption on the basis of interference.

INTERFERENCE

Interference can be understood quite readily in the case of the summing of sine functions. In Fig. 1A are shown five sine functions all with unit amplitude but with different phases: 0 , $\pi/4$, $\pi/2$, $3\pi/4$, and π . In Fig. 1B is shown the sum of these five functions. Since the sum of two sine functions of equal frequency itself is a sine function the sum of multiple such functions is also a sine function. The amplitude of the sum, however, depends on the relative phases of the summed functions. Since the individual sine functions in Fig. 1A all have an amplitude of 1.0 the sum of the amplitudes of the five functions would be 5.0. However, what is found is that the amplitude of the sum is much smaller (as will be shown below it is 2.41). Thus, the amplitude of the sum is not equal to the sum of the amplitudes.

Each of the sine functions in Fig. 1A can be represented by a vector of which the length represents the amplitude and the direction represents the phase. Consequently, the sum of a set of sine functions can be calculated as a vector sum. The x- and y-component of each vector is given as $a \cos(\theta)$ and $a \sin(\theta)$, respectively, where a denotes the amplitude and θ the phase. Thus the addition of two sine functions (with amplitudes of a_1 and a_2 , respectively) becomes $(a_1 \cos(\theta_1) + a_2 \cos(\theta_2))\mathbf{i} + (a_1 \sin(\theta_1) + a_2 \sin(\theta_2))\mathbf{j}$, with $\mathbf{i}$ and $\mathbf{j}$ denoting the unit vectors along the x- and y-directions, respectively. As for the amplitude of the sum of the two sine functions we get $\sqrt{(a_1 \cos(\theta_1) + a_2 \cos(\theta_2))^2 + (a_1 \sin(\theta_1) + a_2 \sin(\theta_2))^2}$. In the case where the amplitudes are 1.0, as in Fig. 1A, we may omit the amplitude values which reduces the expression to $\sqrt{(\cos(\theta_1) + \cos(\theta_2))^2 + (\sin(\theta_1) + \sin(\theta_2))^2}$. For the addition of several sine function all of equal frequency and unit amplitude we get $\sqrt{(\sum_i \cos(\theta_i))^2 + (\sum_i \sin(\theta_i))^2}$. In the case of five functions all with unit amplitude and phase values of 0 , $\pi/4$, $\pi/2$, $3\pi/4$, and π as in Fig. 1 we get:

$$\sqrt{(\cos(0) + \cos(\pi/4) + \cos(\pi/2) + \cos(3\pi/4) + \cos(\pi))^2 + (\sin(0) + \sin(\pi/4) + \sin(\pi/2) + \sin(3\pi/4) + \sin(\pi))^2}$$

$= 2.41$ which is considerable less than the sum of the amplitudes of 5. The vector sum of the five functions in Fig. 1A is shown in Fig. 1C. It is apparent that the length of the vector representing the amplitude of the sum is smaller than the sum of the lengths of the individual vectors representing the individual amplitudes. The difference between the amplitude of the sum and the sum of the amplitudes (i.e., between 2.41 and 5) is the result of interference.

Fig. 1

Fig. 1. (A) Five sine functions all having an amplitude of 1.0 but with different phases: 0, $\pi/4$, $\pi/2$, $3\pi/4$, and π . (B) The sum of the five functions in A which is a sine function with an amplitude of 2.41. This is smaller than the sum of amplitudes of the five functions in A determined separately, which is 5. Thus, the amplitude of the sum is smaller than the sum of the amplitudes. (Note difference in vertical scale in Panels A and B.) (C) Vector representation of the addition of the five functions in A. Each vector has the length of 1.0 corresponding to unit amplitude. In agreement with the phase angles the five vectors have directions of 0, $\pi/4$, $\pi/2$, $3\pi/4$, or π , respectively. As can be seen, the length of the vector marked "SUM" is shorter than the sum of the lengths of the five vectors.

In order to quantify the difference between the amplitude of the sum and the sum of the amplitudes we define the *Relative Amplitude Sum* (RAS) as $|\sum_i F_i| / \sum_i |F_i|$, where F_i denotes the Fourier spectra of the functions which are being combined and $|\cdot|$ denotes the amplitude operator. The difference between $|\sum_i F_i|$

and $\sum_i |F_i|$ is that in the case of the former the functions are summed before the amplitude is calculated whereas in the latter case the amplitudes are calculated before they are summed. [FOOTNOTE 3] In order to illustrate the Relative Amplitude Sum we may return to the example in Fig. 1 where the amplitude of the summed function is 2.41 whereas the sum of the amplitudes in the individual function is 5. This gives a Relative Amplitude Sum of 0.482 (i.e., $2.41 / 5 = 0.482$) which represents a 52 % reduction in the amplitude in the summed functions owing to interference.

The Fourier Transform entails that any signal can be analyzed into series of sine functions. In the present context this means that the adding of two or more stimuli can be considered as the summing of series of sine functions. Consequently, the kind of consideration illustrated in Fig. 1 may apply to the combining of any stimuli of the same spatial dimensions. This includes the combining of target and distractor stimuli in the kinds of stimulus configurations used to explore visual search. When the amplitude of the sum is smaller than the sum of the amplitudes the full amplitudes of all the functions cannot be fully contained in the combined stimulus. Consequently, if we take the sum of amplitudes as measure of stimulus power (see Skottun, 2018) we get that interference may reduce the stimulus power of the stimuli when they are combined.

VISUAL SEARCH STIMULI

Visual search stimuli consist of a target stimulus and one or more distractor stimuli. An example of such stimuli is shown in Fig. 2A. The total stimulus consisted of 64 x 64 pixels. The target was a cross 7 pixels high and 7 pixels wide and the distractors were L-shaped also subtending 7 x 7 pixels. The positions of the stimulus elements were randomized. The exact positions of the stimulus elements was found to have little influence upon the results. This is consistent with observations of Skottun (2017a. See Figs. 3c & 4b of that paper. See also Fig. 3 of Skottun, 2017b).

Relative Amplitude Sum. In typical experiments the number of stimulus elements—the set size—constitutes the independent variable. What is sought in the present context is to determine how the number of stimulus elements determines the Relative Amplitude Sum (RAS). Denoting the Fourier spectrum of the target by T and the Fourier spectrum of the i th distractor by D_i we get $RAS = \sum |T + \sum_i D_i| / (\sum |T| + \sum_i |D_i|)$. Where $\sum |T + \sum_i D_i|$ denotes the sum of the amplitudes in the Fourier spectrum of the target plus the Fourier spectrum of all the distractors, whereas $\sum (|T| + \sum_i |D_i|)$ denotes the sum of the amplitude spectrum of the target plus the sum of all the amplitudes in the spectra of the distractors determined separately.

Fig. 2

Fig. 2. (A) An example of the simulated stimuli. The stimuli spanned 64 x 64 pixels. Target stimuli were crosses with dimensions of 7 x 7 pixels and distractor elements were L-shaped elements also 7 pixels wide and high. (The letter "A" is not part of the stimulus.) (B) Relative Amplitude Sum (RAS) as a function of set size. The data represent averages of 1000 repetitions. (C) Relative Norm as a function of set size. In Panels B and C filled symbols give data obtained for interference between all elements and open symbols represent results for when interference is between the target stimulus and the set of distractor elements when these are considered together as a single background. The set size represents the total number of elements including the target.

The filled symbols in Fig. 2B show the Relative Amplitude Sum as a function of set size. As can be seen, the Relative Amplitude Sum decreases monotonically with set size. For a set size of 12 it is 0.25. If we assume that the sum of amplitudes is a valid measure of stimulus power this would mean that for this stimulus there is a 75 % reduction of stimulus power owing to interference between the elements. Were we to assume that all the elements are affected equally by interference we get that the stimulus power of each element in this set has been reduced by 75 % relative to the stimulus power of the same element when it is being assessed in isolation. These estimates, it should be emphasized, are based on the assumption that interference takes place between all stimulus elements.

Some tasks involving the detection of a target embedded in a set of distractors are very easy. An example would be detecting a red target in a field of green distractors. In such cases it would seem the task ought to be characterized as one of detecting a target stimulus presented upon a background made up of a set of distractors. That is to say, the set of distractors together ought to be considered as an entity, namely the background. This suggests another mode of analysis since in this case adding distractors to the set means adding elements to the background. According to this view the amplitude sum of the background would become $|\sum_i D_i|$ (instead of $\sum_i |D_i|$) making the $RAS = \sum |T + \sum_i D_i| / \sum (|T| + |\sum_i D_i|)$ (rather than $RAS = \sum |T + \sum_i D_i| / \sum (|T| + \sum_i |D_i|)$). In other words, when treating the set of distractors as a single background the Fourier spectra of the distractors are summed before the amplitudes are determined. The effect of set size on the RAS estimated in this manner is shown in Fig. 2B with open symbols. In this case the RAS values are slightly below 1.0 but stay relatively constant in the range 0.70 - 0.81 and show a weak tendency to increase with the number of distractors. (That is, when excluding the case of a set size of 1 in which the set consists only of the target stimulus.)

From Fig. 2B is apparent that the effect of set size depends on whether the stimuli are considered as a set of elements (filled symbols in Fig. 2B) or as a target presented on a single background consisting of a number of distractor elements (open symbols in Fig. 2B). It should be pointed out that the two data sets in Fig. 2B are obtained with similar stimuli. The only difference is in the way they were analyzed.

[FOOTNOTE 4]

Norm. In the above the sum of amplitudes were taken as the measure of stimulus power. An alternative measure would be the norm. What makes the norm interesting in the present context is that it can be generated from the space domain representation of the stimuli. Thus, if interference can be demonstrated

based on the norms this would entail that it is not the result of the Fourier Transform (that is, it does not depend on the use of sine functions as basis functions).

The norm is the length of a vector. It is the square root of the inner product of the vector with itself. For a vector f it is defined as $\|f\| = \sqrt{\sum_i f_i^2}$ where f_i is the i th component of f . [FOOTNOTE 5] In the case of interference between all elements the *Relative Norm* was defined as $\|T + \sum D\| / (\|T\| + \sum \|D\|)$, where T denotes the target and D the distractors. In the case where the background was treated as unit the Relative Norm was calculated as $\|T + \sum D\| / (\|T\| + \|\sum D\|)$.

In Fig. 2C is shown the Relative Norm as a function of set size. In the case of interference between all elements (filled symbols) there is a monotonic decline in Relative Norm with set size. In the case where the distractors are considered together as a single background the Relative Norm values are slightly below 1.0 and show a slight increase with set size (open symbols). These results are in close agreement with those for the Relative Amplitude Sums (Fig. 2B) which entails that the present results are not limited to data generated with Fourier Transforms.

Response Time. The effect of set size in psychophysical visual search experiments is typically given in terms of response time. An example is shown in Fig. 3A in which are re-plotted data from Fig. 2 of Wolfe et al. (1992). The filled symbols give data for detecting an element tilted 20 degrees embedded in a heterogeneous set of distractors containing elements tilted at angles of 0, 40, 60, 80, -20, -40, -60, and -80 degrees. The open symbols show data for the same target presented in a homogeneous set of only vertical distractors. In the former case the response time increases monotonically with set size whereas in the latter case the response time is substantially independent of set size.

Up until this point the present analyses have described properties which are wholly in the stimuli. That is to say, properties which exist independently of the visual system or whether or not the stimuli are being seen. We might say they describe the "physics of the stimuli". To derive response time from stimulus power obviously requires involvement of the visual system. This makes it necessary to make at least one assumption about the relationship between stimulus power and response time. What seems highly plausible would be for higher stimulus power to yield a shorter response time. This would be consistent with the observations of Murray & Plainis (2003) who found higher contrast to give shorter response time. The simplest relationship would be for response time to be the inverse of stimulus power. Based on this assumption response times were simulated from the results in Fig. 2B and 2C for set sizes of 1, 4, 8, and 12 elements. These estimates

are shown in Fig. 3B and 3C. As can be seen, when the stimuli are considered as a set of elements (which all interact with each other) the inverse of the Relative Amplitude Sum (filled symbols Fig. 3B) and the inverse of the Relative Norm (filled symbols Fig. 3C) both increase monotonically with set size. On the other hand, when the stimuli are considered in terms of a target and a single background consisting of a set of distractors the inverse of the Relative Amplitude Sum (open symbols Fig. 3B) and the inverse of the Relative Norm (open symbols Fig. 3C) are both substantially independent of set size.

When comparing the results in Panel A of Fig. 3 with those in Panels B, and C of this figure it becomes apparent that psychophysical results obtained with heterogeneous stimuli (filled symbols in Fig. 3A) are quite similar to the estimates based on interactions between all elements (filled symbols in Fig. 3B and 3C) and that psychophysical data for homogeneous sets of distractors (open symbols in Fig. 3A) are quite similar to estimates based on the assumption that the set of distractors make up a single background (open symbols in Fig. 3B and 3C).

DISCUSSION

The present analyses have sought to estimate interference in multi-element stimulus configurations. Two scenarios have been explored: (1) All elements interfere with each other, and (2) A single background consisting of several elements interferes as a unit with a single target. In the former case it is found that the interference increases monotonically with the number of elements in the stimulus configuration. In the latter case it is found that the interference is relatively mild and remains relatively independent of the number of elements making up the background. This means it is possible to obtain either of these scenarios depending upon how the stimuli are analyzed. In either case, it needs to be emphasized, the interference effects are in the stimuli. That is, they exist independently of whether or not the stimuli are seen or activate any visual system.

Obviously, visual search experiments are visual experiments and thus involve vision. This, however, does not preclude interference from taking place in the stimuli. That is, there is no conflict between the stimuli being seen and interference taking place in the stimuli.

Fig. 3

Fig. 3. (A) Response time as a function of set size re-plotted from Fig. 2 of Wolfe et al. (1992). Filled symbols are for an elongated target tilted at 20 degrees embedded in a heterogeneous field of distractors tilted at angles of 0, 40, 60, 80, -20, -40, -60, and -80 degrees. Open symbols are for a 20 degrees target embedded in a homogeneous set of distractors all with 0 degrees orientation. (B) The inverse of the Relative Amplitude Sum as a function of set size. (C) The inverse of the Relative Norm as a function of set size. In Panels B and C filled symbols give data obtained for interference between all elements and open symbols represent results for when interference is between the target stimulus and the set of distractor elements considered as a single background.

The results of visual search experiments have typically been given in terms of response time. In order to show the potential relevance of the present observations comparisons with psychophysical results were made based on the simple assumption that the response time and stimulus power are inversely related. The resulting estimates are shown in Fig. 3B and 3C and show quite close matches to the results from psychophysical results as re-plotted in Fig. 3A.

In experiments where response times increase with set size it has generally been assumed that the effect is a consequence of the shifting of attention. Although this may seem plausible one needs to contrast this account with one in which attention plays no role. In other words, one must not only ask what the effect of set size would be if attention were involved but one must also ask what the effect of set size would be if attention were not involved. Since attention plays no role in present analyses they provide one possible answer to this question.

As has been pointed out previously (Skottun, 2017a, 2018) interference does not alter the physical images of the stimuli. That is, a target elements remains the same target element whether it is presented along with distractor elements or not. What is changed is its stimulus power. In the present analyses two measures of stimulus power were explored: Amplitude sums and norms. For these two measures the influence of interference was assessed based on the Relative Amplitude Sum and the Relative Norm, respectively. These values are for the whole stimulus arrays. In visual search the task is to respond to some aspect of the target stimulus. Thus, the central issue is how interference affects the stimulus power of this stimulus. In a case where all the stimulus element were identical the Relative Amplitude Sum and Relative Norm would represent the relative stimulus power in each element (i.e., stimulus power of each element relative to when it is element is presented alone). In the present analyses the target and the distractor stimuli are relatively similar. (It would seem plausible that in order for distractors to distract they need to resemble the target to some degree.) However, they need to differ to some degree in some respect. Due to this minor difference it is possible that interference affects target and masking stimuli differently. However, since the sum of the amplitudes in the target and each of the distractor elements are quite similar (176.1 for the target vs 171.4 for a distractor) and the norms are identical (both 3.605) it would seem that the present Relative Amplitude Sum and Relative Norm values would provide reasonably close estimates of the reduction of the stimulus power of the target stimuli resulting from the presence of distractor stimuli.

In summary: The present analyses demonstrate that due to interference the presence of distractor stimuli may reduce the stimulus power of stimulus elements in visual search stimuli. The effect may be small and

relatively independent of set size or it may be substantial and show a pronounced monotonic reduction with set size. This depends on whether interference is calculated between a target and a single background or between all stimulus elements. These effects are in the stimuli and exist irrespective of whether or not the stimuli are seen or activate any visual system. Nor do they involve attention. By assuming that response time is inversely related to stimulus power it is possible to generate functions relating response time to set size which resemble closely results from psychophysical experiments.

FOOTNOTES

1. It has been proposed that interference takes place in filters and that these correspond to visual neurons. This represents a fundamental misunderstanding. To recognize this one should consider the simple case of adding two sine gratings of the same amplitude, same spatial frequency, and same orientation. If the two gratings are 180 degrees out of phase the troughs in the first gratings will coincide with the peaks in the second and vice versa making the two gratings cancel. The result will be a uniform field with no variation in luminance. (For an illustration of the adding of sine functions see Fig. 1 of Skottun, 2017.) This cancelation represents a case of interference. It is simply a matter of the physics of the stimuli and takes place in the stimuli and occurs independently of whether or not the stimuli are filtered, seen, or activate visual neurons.
2. For a discussion of the concept of "stimulus power" see Skottun (2018).
3. The reason for the difference is that amplitudes generally do not add linearly. That is, in the case of two Fourier spectra, A and B , we generally have $\sum |A + B| < \sum |A| + \sum |B|$. We only have $\sum |A + B| = \sum |A| + \sum |B|$ when A and B have identical phase spectra (something which generally is not the case for visual stimuli). (Amplitude spectra are, in this regard, different from Fourier spectra which add linearly, i.e., for which $\sum (A + B) = \sum A + \sum B$.)
4. It has been pointed out that Relative Amplitude Sum ought to be calculated from amplitude spectra in which the dc value is set to zero (Skottun, 2018). In the present case this makes very little difference since the average luminance is very small. To give an example, in the case of interference between all elements the Relative Amplitude Sum for 12 elements were 0.2525 and 0.2517 for the dc value retained and the dc value set to zero, respectively.
5. The space domain norm of a signal is equal to the norm of its Fourier Transform. Since the Fourier Transform is made up of complex numbers it is necessary to take the inner product of the vector with its complex conjugate. For a space (or time) domain signal, f , we thus get $\|f\| = \sqrt{\sum F_i \overline{F_i}}$, where F_i is the i th element in Fourier Transform of f and the overline denotes the complex conjugate.

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