Notes and Comment

An element in the visual field is just a conjunction of attributes: A critique of Bundesen (1991)

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Nissen (1985) presented results showing that in partial-report experiments, selection by location was different from selection by color or by shape. Bundesen (1991) presented a reinterpretation of these results, claiming that they can also be explained by a model in which location selection is treated on a par with selection by color or by shape. We will show that the analysis given by Bundesen is based on a special relation between an "element" in the visual field and its location, which in fact reduces the expressions given by Bundesen to those given by Nissen. Furthermore, we will show that in Bundesen's theory, it is assumed that in the process of perceptual categorization an element in the visual field can be referred to without the use of one of its attributes. This assumption is untenable from a theoretical point of view. In all, the results presented by Nissen can still be regarded as evidence for the difference between selection by location and selection by color or by shape.

An important issue in the theory of visual selective attention is the question of whether selection by location is different from selection by other attributes like color or shape. In models of visual attention presented by, for example, Eriksen (1990), Treisman (1988), and van der Heijden (1992), attention is directed primarily by information on the location of an object. On the other hand, Bundesen (1990) presented a theory in which selection by means of location is treated on a par with selection by color or by shape (for similar views, see, e.g., Broadbent, 1971; Duncan, 1984; Kahneman, 1973).

Nissen (1985) reported results that indicated that selection of a shape on the basis of a color cue was mediated by location information. This result seemed to be in favor of models in which location is the dominant attribute for selection. However, Bundesen (1991) claimed that Nissen's results can also be explained by a model in which

selection by location is not different from selection by color or by shape. We will show that his analysis is based on two assumptions. The first implicit assumption concerns the use (in the process of perceptual categorization) of some form of abstract identity of an element in the visual field, distinct from attributes like location, color, or shape. The second assumption concerns the relations between that abstract element and each individual attribute, and in particular the difference between location and other attributes like shape and color, in this respect.

In our view, the first assumption is invalid because an object or an element in the visual field is only the conjunction of attributes (or features). Therefore, in the process of perceptual categorization, an element cannot be referred to without the use of (at least one) attribute, which implies that this attribute is already known to the subject. Furthermore, the special relation between location and the element in Bundesen's (1991) analysis is in fact a reintroduction of the special role of selection by location in the analysis given by Nissen (1985). Before explaining these points in more detail, we will first briefly describe the findings reported by Nissen and the reinterpretation of these findings given by Bundesen.

Nissen's Findings

Nissen (1985) studied selection by location and by color in two experiments. In both experiments, the stimulus consisted of a display of four colored shapes. The shapes and colors were all different. In the first experiment, the subject was cued with a location and was requested to report the color at that location, or a color was given as a cue and the location had to be reported. Nissen found no difference in accuracy of report between the two conditions. Thus, the probability of selecting the color given the location was comparable to the probability of selecting the location given the color. In Nissen's symbols,

$$P(C|L) = P(L|C).$$

In the second experiment, the same design was used, again in two conditions. In the first condition, a location was given as a cue, and the task consisted of naming the color and the shape at that location. The probability of correctly selecting the color and the shape given the location [$P(C \& S|L)$] was approximately equal to the product of the marginal probability of reporting the color given the location [$P(C|L)$] and the marginal probability of reporting the shape given the location [$P(S|L)$] in this experiment. In terms of these probabilities,

$$P(C \& S|L) = P(C|L) \times P(S|L).$$

In the second condition, a color was given as a cue, and

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location and shape were the attributes to be reported. In this condition, the combined probability $[P(L \& S|C)]$ was different from the product of the marginal probabilities $[P(L|C) \text{ and } P(S|C)]$. On the basis of the results of Experiment 1 and the first condition of Experiment 2, Nissen (1985) hypothesized that the selection of the shape given the color was mediated by the selection of the location given the color. In this view, a subject first selected the location at which the color appeared with a probability $P(L|C)$ and then selected the shape at that location with a probability $P(S|L)$. If so, the probability of correctly selecting the location and the shape of a cued color should be given by

$$P(L \& S|C) = P(S|L) \times P(L|C).$$

The outcome of Experiment 2 confirmed this prediction.

Nissen's (1985) results seem to indicate that when location is given as a cue, the selection of shape and color is independent, but when color is given as a cue, the selection of shape is mediated by the selection of location, at least when both attributes have to be named. This would indicate that in visual attention, there is an asymmetry between selection by location and selection by color or by shape, with location as the dominant form of information on which visual selective attention is based.

Analysis by Bundesen

The role of the element in Bundesen's theory. The analysis of Nissen's (1985) results by Bundesen (1991) is an attempt to explain these findings in terms of a model in which selection by location is treated on a par with selection by color or by shape, as in the theory of visual attention presented by Bundesen (1990).

To illustrate the analysis given by Bundesen (1991), consider the way in which Bundesen and Nissen (1985) introduce the probabilities $P(L|C)$ and $P(S|L)$. Nissen (1985, p. 215) writes: "subjects determined the location of the cued color with probability $P(L|C)$ and they determined the shape at that location with probability $P(S|L)$." Bundesen (1991, p. 87) writes: "the subject first determined the location of the *element* in the cued color with probability $P(L|C)$ and then determined the shape of the *element* at that location with probability $P(S|L)$ " (italics ours). The descriptions are almost the same, except for the (repeated) insertion of the phrase "of the element" in Bundesen's formulation. It is the concept of "element" that is critical in Bundesen's theory of attention and in his analysis of Nissen's results.

The words "element," "object," or "item" are often used in the literature on visual attention to denote a conjunction of attributes (or features) in the visual field (e.g., see van der Heijden, 1992, p. 275). However, in Bundesen's (1990, 1991) theory, the word "element" attains a different meaning. In his theory, visual recognition and attention consist of making perceptual categorizations of the form " x belongs to F ," where x is an element in the visual field and F is a perceptual category (i.e., attribute). Thus, there is something in the visual field that is

called an "element" (x) and that functions in the process of perceptual categorization. About that element, categorizations of the form " x is red," " x is circular," and " x is above fixation" can then be made. This indicates that in the process of perceptual categorization, the element x does not just denote the conjunction of the attributes location, color, and shape, but refers to an identity distinct from these attributes.

The separate identity of an element x , distinct from its attributes, is even more explicit when Bundesen (1991) introduces probabilities. He writes (1991, p. 88): "Let the probability of sampling the *correct* color categorization of an element be a constant p_C , let the probability of sampling the *correct* shape categorization of an element be a constant p_S , and let the probability of sampling the *correct* location categorization of an element be a constant p_L " (italics ours). The word "correct" indicates that it is also possible to sample incorrect attributes of an element x . Thus, the theory assumes that we first identify an element x in the visual field and then select the attributes color, shape, and location (e.g., red, circular, and above fixation). In particular, the theory allows for the possibility that one could select the incorrect location, color, and shape of element x . That is, one could select *all three* attributes of an element x incorrectly, which shows that none of the attributes is used to identify the element x .

Reinterpretation of Nissen's results. On the basis of his theory, Bundesen (1991) analyzes the results of Nissen (1985). The values p_C , p_S , and p_L defined above represent the probabilities that the attributes color, shape, and location of an element x were identified during the perceptual stage. Because Bundesen assumes that perceptual confusions are negligible, $1 - p_C$, for instance, represents the probability that no color was identified for the element x . In the report stage, subjects will guess a color in these cases, with a probability of $(1 - p_C)/4$ of reporting the correct color. Therefore, the probability of reporting the correct color of an element is $p_C + (1 - p_C)/4$. Similarly, the probability of reporting the correct shape of an element is $p_S + (1 - p_S)/4$. For location, the situation is different. Bundesen assumes that location identification in visual perception is almost always correct. Thus, $p_L = 1$, which then also represents the probability of reporting the location of an element.

The probabilities $p_C + (1 - p_C)/4$, $p_S + (1 - p_S)/4$, and $p_L = 1$ therefore represent the strength of the connections between an element x and its attributes in Bundesen's (1991) model (see Figure 1a). It is further assumed in the model that these connections are two-way, that is, they express both the probability of correctly reporting the attribute when the element is known as well as the probability of correctly determining the element when the attribute is known.

On the basis of the connections between an element and its attributes, the reinterpretation of Nissen's (1985) results by Bundesen (1991) is easily constructed. In the case of Experiment 1, the probability of reporting the color

(a)

(b)

Figure 1. (a) Relations of the attributes color (C), location (L), and shape (S) with the element x in Bundesen's (1991) analysis. Each link represents the probability of identifying the element given the attribute or of naming the attribute when the element is known. (b) Relations between the attributes when location is identical with the element x (contraction of the link between L and x in Figure 1a).

when a location is given is represented by Bundesen as the product of the probability of determining the element given the location ($p_L = 1$) and the probability of reporting the color when the element is known [$p_C + (1-p_C)/4$]. Thus,

$$P(C|L) = [p_C + (1-p_C)/4] \times 1.$$

We write the result for $P(C|L)$ in this way to demonstrate that it is the result of a product, which is otherwise concealed because $p_L = 1$. It is important to stress this point because it demonstrates the use of the (separate) identity of the element x in Bundesen's analysis.

The use of the element x in the analysis can be made even more explicit by giving the derivation of $P(C|L)$ in general probabilistic terms. The probability of determining the element x when its location is given can be denoted by $P(x|L)$, and the probability of reporting the color when the element x is known can be denoted by $P(C|x)$. Because $P(x|L)$ and $P(C|x)$ are assumed to be independent by Bundesen (1991), $P(C|L)$ is given by

$$P(C&x|L) = P(C|x) \times P(x|L),$$

where we have replaced $P(C|L)$ by $P(C&x|L)$, because in Bundesen's analysis, the probability of reporting the color when the location is given is actually the probability of determining the element and reporting the color when the location is given.

The expression for $P(C&x|L)$ is easily constructed using Figure 1a. When a location is given and the color

at the location has to be reported, start with L and trace the path to C (which always runs through x). The path from L to x is given by $P(x|L)$, the path from x to C is given by $P(C|x)$, and the whole path from L to C is given by $P(C&x|L)$. The whole path is always the product of its subpaths, which in the case of $P(C&x|L)$ gives the expression presented above. This procedure can be used for each expression given by Bundesen (1991).

Therefore, $P(L|C)$ is represented by

$$P(L&x|C) = P(L|x) \times P(x|C),$$

by tracing the reverse path from C to L in Figure 1a. As a result of the two-way connections between an element and its attributes (see above), $P(x|L) = P(L|x)$ and $P(x|C) = P(C|x)$. From this, it follows that

$$P(C&x|L) = P(L&x|C).$$

Or

$$P(C|L) = P(L|C)$$

in Bundesen's (1991) terminology.

The Critical Condition

We will now use the procedure outlined above to analyze $P(L&S|C)$, which represents the main result of the second experiment reported by Nissen (1985). Starting at C in Figure 1a, the element x is determined with the probability $P(x|C)$. From x , the attributes location and shape are determined with the probabilities $P(L|x)$ and $P(S|x)$, respectively. Taking the product we have in Bundesen's (1991) analysis,

$$P(L&S&x|C) = P(L|x) \times P(S|x) \times P(x|C), \quad (1)$$

where we again have replaced $P(L&S|C)$ with the correct expression $P(L&S&x|C)$.

The main result found by Nissen (1985) was:

$$P(L&S|C) = P(S|L) \times P(L|C). \quad (2)$$

In the analysis given by Bundesen (1991), $P(S|L)$ is given by (see Figure 1a)

$$P(S&x|L) = P(S|x) \times P(x|L),$$

and $P(L|C)$ is given by

$$P(L&x|C) = P(L|x) \times P(x|C).$$

Therefore, in Bundesen's analysis, Equation 2 is equal to

$$P(L&S&x|C) = P(L|x) \times P(L|x) \times P(S|x) \times P(x|C), \quad (2a)$$

where we used $P(x|L) = P(L|x)$. A comparison of Equations 1 and 2a shows that these two expressions *can only be equal* in Bundesen's reinterpretation if

$$P(L|x) \times P(L|x) = P(L|x),$$

that is, if $P(L|x)$ is *identically* equal to 1. We will return later to this important result.

The other expressions given by Bundesen (1991) can be constructed in a similar way. However, our objections

to the reinterpretation given by Bundesen can be made on the basis of the expressions presented above, which represent the main result found by Nissen (1985) concerning the difference between selection by location and selection by color or by shape. Naturally, the objections also apply to the other expressions given by Bundesen.

Evaluation

We will summarize our critique of the analysis given by Bundesen (1991) in three points:

The identity of element and location in Bundesen's analysis. We demonstrated above that $P(L|x)$ is *identically* equal to 1 in the analysis given by Bundesen (1991). This is an important point because it shows that $P(L|x)$ does not equal 1 because of some (variable) external circumstance (e.g., because location categorization is very fast, as Bundesen suggests), but out of necessity in order for the analysis to hold. This means that there is a necessary one-to-one correspondence between an element and its location in Bundesen's theory: Whenever the location is known, so is the identity of the element, and vice versa. In other words, location and element are indistinguishable. Therefore, Figure 1a equals Figure 1b, which corresponds to the analysis given by Nissen (1985) if we assume (as Bundesen does) that the connections are two way with the same value (see above). Thus, in terms of Figure 1b, $P(C|L) = P(L|C)$ and $P(L \& S|C) = P(S|L) \times P(L|C)$.

The fact that location and element are indistinguishable (and therefore one of them is redundant) can also be shown using Figure 1a (Bunden's [1991] original scheme): Let A be any attribute of the element x ; then, using $P(x|L) = P(L|x) = 1$,

$$P(L|A) = P(L|x) \times P(x|A) = P(x|A)$$

and

$$P(A|L) = P(A|x) \times P(x|L) = P(A|x).$$

Because A is arbitrary, it follows that L is identical to x .

Symmetry versus asymmetry. The fact that the element x is identical to location and therefore redundant is not a (removable) coincidence, but a direct result of the data that have to be modeled. Consider Figure 1b. This figure shows some form of asymmetry between location, on the one hand, and color or shape, on the other. (In fact, symmetry would exist if C and S were directly connected, so that each attribute could directly gain access to the other attributes. Only then would location lose its mediary role between color and shape.) Figure 1b (without the redundant element x) corresponds to the predictions given by Nissen (1985). The important point is that *these* predictions were confirmed by the data (which is not denied by Bundesen, 1991). In other words, the data contain a form of asymmetry between location and the other attributes, which is precisely what the expressions given by Nissen capture.

In this respect, Bundesen's (1991) analysis can be seen as an attempt to explain a form of asymmetry in the data on the basis of a theoretically assumed symmetry (that is, in *his theory*, location is treated on a par with color

and shape). Such an attempt is destined to fail because asymmetry cannot be explained solely on the basis of symmetry. This is what our analysis of Bundesen's attempt shows: the (necessary) asymmetry between location and the other attributes is reintroduced through the spurious element x , which has to be indistinguishable from location to explain the asymmetry in the data. Thus, in Bundesen's analysis, location is in fact *not* treated on a par with color and shape. However, the special role of location is hidden in the specific relation between location and the spurious element x .

The use of the element in Bundesen's theory. Because an element is just a conjunction of attributes, an element is identified by (at least) one of its attributes. For instance, in Bundesen's (1991) analysis, an element is identified by its location, because the abstract identity he uses is in fact indistinguishable from location, as we showed above. The use of a separate identity of an element, distinct from its attributes, introduces a concept that has no basis in reality and leads to confusion about the relations between the attributes in visual attention, as in the case of Bundesen's analysis.

Therefore, it is important to eliminate the notion that in the process of perceptual categorization, an element x can be identified without referring to one of the attributes. To see why, consider again the theory presented by Bundesen (1990, 1991). In Bundesen's theory, visual recognition and attention consist of making categorizations of the form " x belongs to F ," where x is an element and F is an attribute (see above). In particular, if there are four elements (objects or items) in the visual field, the theory first assumes that each element x is labeled. Thus, we have x_i , with $i = 1, 2, 3$, or 4. Then, for each element x_i , the correct categorizations C_i (color), S_i (shape), and L_i (location) are sampled, each with a particular probability (see above).

Labeling an element in the visual field (or any object, for that matter) requires a process of discrimination. Objects that are indiscriminable cannot be labeled; that is, they cannot be identified or pointed at. The only way to discriminate elements in the visual field is to refer to at least one attribute. (To see why, imagine a visual field with four "elements," each with the three attributes location, color, and shape, as in Nissen's [1985] experiments. Elimination of these attributes leaves an empty field.) Therefore, the label of the element x_i is always identical to at least one of the attributes color, shape, or location. In terms of Bundesen's (1991) theory, this means that at least one of the categorization probabilities is identical to 1. Thus, for a visual field with the elements 1, 2, 3, and 4, at least one categorization (i.e., color, shape, or location) is already known. In particular, it is not possible that *all three* attributes of an element can be selected incorrectly, as is assumed in Bundesen's theory (see above), because at least one of these attributes has to be used to identify the element in the first place (see, e.g., the quote from Nissen, 1985, p. 215). Of course, this is what we demonstrated above: In Bundesen's reinterpretation of the results presented by Nissen, the elements

were in fact labeled with their location, because p_L was identically equal to 1. From a theoretical point of view, the elements can also be labeled with color or shape. However, Bundesen had to choose location in order to explain the asymmetrical results reported by Nissen (see above).

The fact that only attributes can be used to label (identify) an element is also apparent from the design of experiments in the study of visual attention. Usually, as in the experiments reported by Nissen (1985), a subject is requested to report one or more attributes of a target in the display. For this purpose, the target has to be identified by the subject. Invariably, an attribute of the target is therefore given as a cue, which allows the subject to identify the target. Thus, for instance, one can ask a subject to report the shape of, say, the red element in the display. One can also ask the subject to report the shape and location of the red element. It is even possible, although partly trivial, to ask a subject to report the shape, location, and color of the red element. But it makes no sense to ask a subject to report the shape, location, and color of, say, element x_1 , because element " x_1 " has no meaning for the subject. Yet, in Bundesen's theory, such a question is possible, because in his theory the categorizations shape, location, and color are made for each element x_i .

Finally, Bundesen (1990, 1991) claims that his notion of an element in the visual field is similar to the one given by, for instance, Kahneman (1973). However, this is a misrepresentation of Kahneman. Kahneman extensively discusses the process of preattentive discrimination by which the visual field is segmented into units (or elements). At no point does he refer to any form of abstract identity of these units. Instead, he clearly states that "pre-attentive discriminations refer to obvious physical features" (Kahneman, 1973, p. 75), although occasionally more complex analyses (e.g., semantic decoding) are used.

Conclusion

Our analysis shows that the attempt made by Bundesen (1991) to explain the results reported by Nissen (1985) on the basis of a model in which selection by location is treated on a par with selection by color or by shape has failed. Furthermore, our analysis shows that the model of Bundesen (1990) contains a serious flaw in the form of the abstract identity of an element, separate from its attributes, that is used in the process of perceptual categorization.

The results reported by Nissen (1985), therefore, can still be regarded as empirical evidence for the view that location selection is a dominant mode of selection in visual attention.

Apart from empirical evidence such as that presented by Nissen (1985), there is also a theoretical reason why location selection might be different from selection by any other attribute: Unlike any other attribute, location is always specific for each object in the visual field. Consider again the design used in the experiments reported by Nissen. It is possible for each object in the display to have the same color (e.g., red), or the same shape (e.g., circular), or even the same conjunction of color and shape (e.g., red circles). However, for objects in the visual field to be distinct, each needs to have its own (specific) location different from other locations.

For a system that has evolved to deal with the general circumstances of everyday life, a reliable mode of selection could therefore well be selection by location, especially if the survival of the system depended on the success of the selection process.

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