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Independent encoding of colors and shapes from two stimuli

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Observers were presented with brief exposures of pairs of colored objects (letters) and asked to report both the color and the shape of each object. Several observers showed strikingly clear evidence of nearly perfect stochastic independence between reports of the four features (two colors and two shapes). For instance, the probability that the shape of a given object could be reported seemed independent of (a) whether the color of the object could be reported and (b) whether features of the other object could be reported. Such stochastic independence is predicted by many parallel-processing models (e.g., Bundesen, 1990). However, the results are difficult to reconcile with simple serial models in which the encoding of one object is completed before the encoding of another object is begun.

In this article, we introduce a simple experimental technique for investigating both dependencies in processing of different features of the same object and dependencies in processing of features from different objects. In the reported experiment, each stimulus display showed a pair of colored letters, one to the left and one to the right of fixation. The exposure was so brief that observers rarely succeeded in encoding the stimuli in such a way that both the color and the shape of each letter could be correctly reported. We tested whether the probability that the shape of a given letter was correctly reported depended on whether the color of the letter was correctly reported. We also tested whether the probability that a feature (shape or color) of one of the letters was correctly reported depended on whether features of the other letter were correctly reported. Mutual independence between encoding of each of the four features (two colors and two shapes) would be a strong constraint on models of visual attention and short-term memory (for reviews, see, e.g., Bundesen, 1996; Pashler, 1998a, 1998b; see also Palmer, Verghese, & Pavel, 2000).

METHOD

Participants

Five students and 3 members of the staff at the University of Copenhagen participated as observers. Their ages ranged from 25 to 53 years with a mean of 35 years. All participants reported that they had normal or corrected-to-normal visual acuity and normal color vision.

Procedure

Each observer was tested individually in one experimental session, which consisted of 200 trials. Short breaks were held between blocks of 50 trials. On the day before the actual experiment, the observer participated in a practice session comprising 100 trials, in which similar stimulus material was employed to familiarize the observer with the apparatus and procedure.

The observer was seated in front of a computer-driven video screen (SVGA with a refresh rate of 70 Hz) at a viewing distance of 80 cm in a semidarkened room. A small (2 × 2 mm) gray (CIE x, y coordinates of 0.29/0.28; 4.8 cd/m^2) fixation cross was permanently visible at the center of the screen.

Each trial was initiated by the observer. When adequately fixated, the observer pressed a key to produce an immediate exposure of a letter pair on the video screen. The exposure duration was 29 msec, and the letter pair was followed by a 500-msec mask. The four features (two colors and two shapes) of a letter pair were chosen at random, independently of each other, and for each letter, the six possible colors were equally likely and the 25 possible shapes (letter types) were equally likely. These facts were pointed out to the observer during the practice session. The observer was asked to pay equal attention to the two letters and try to report the color and the shape (identity) of each letter, but refrain from pure guessing. It was emphasized that the two feature dimensions (color and shape) were equally important. To make the response procedure as easy as possible for the observer, the reports were spoken by the observer and typed by the experimenter. Order of report was free, but the observer indicated whether a report of a feature referred to the letter on the left or the letter on the right.

Stimuli

The two letters in a stimulus pair were centered 48 mm (3.4º of visual angle) to the left and to the right of the fixation cross. Each letter covered about 54 mm (3.9º) vertically and 34 mm (2.4º) horizontally. The letter was red (CIE x, y coordinates of 0.61/0.34; 1.5 cd/m^2), yellow (CIE x, y coordinates of 0.40/0.50; 11.9 cd/m^2), green (CIE x, y coordinates of 0.29/0.58; 1.1 cd/m^2), blue (CIE x, y coordinates of 0.16/0.06; 0.7 cd/m^2), purple (CIE x, y coordinates of 0.28/0.14; 4.4 cd/m^2), or gray (CIE x, y coordinates of 0.28/0.28; 7.9 cd/m^2) on a black (0.0 cd/m^2) background. The possible letter types were A–Z, with W excluded. All letters were uppercase.

Mask

The mask consisted of two randomly patterned rectangles, one for each of the stimulus letters. Each rectangle filled an area of 64 mm (4.6º) vertically × 48 mm (3.4º) horizontally, which covered up the location at which the corresponding stimulus letter had appeared.

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Table 1
Observed Probabilities of Correct Report

Observer	Left Shape	Left Color	Right Shape	Right Color	*r*
S1	.83	.57	.91	.67	.995
S2	.93	.81	.90	.77	.993
S3	.84	.69	.61	.69	.991
S4	.74	.56	.86	.65	.976
S5	.85	.32	.68	.36	.950
S6	.70	.65	.45	.59	.843
S7	.66	.65	.58	.49	.777
S8	.71	.46	.72	.39	.734
M	.78	.59	.71	.57	

Note—The observed probabilities in the table are the proportions of trials with correct reports for each of the four features (two colors and two shapes) of a pair of colored letters, one to the left and one to the right of fixation. Predicted probabilities of 16 possible types of report (listed in Table 2) were calculated by assuming mutual independence between reports of the four features. Values of *r* are Pearson product–moment correlations between observed and predicted probabilities across the 16 types of report.

The rectangle was made up of three types of square-shaped (3 × 3 mm) gray cells with CIE *x*, *y* coordinates of 0.31/0.28, 1.0 cd/m^2; 0.29/0.28, 2.5 cd/m^2; and 0.29/0.28, 4.8 cd/m^2, respectively.

RESULTS

Correct Reports

The observed probability of correct report of a given feature (i.e., the proportion of trials in which the feature was correctly reported) is shown in Table 1 for each observer and each of the four features. On the strong assumption that reports of the four features are mutually independent, the probabilities of each of the $2^4 = 16$ possible combinations of correctly and not correctly reported features (listed in Table 2) should be predictable from the indicated probabilities of report of the individual features. For example, for Observer S1 in Table 1, the probability of correct report of both the shape and the color of the left-hand letter and the shape but not the color of the right-hand letter (Report Type 12 in Table 2) should equal $(.83)(.57)(.91)(1 - .67) = .14$.

Many observers showed strikingly close fits between the observed probabilities for each of the 16 types of report and the predictions obtained by assuming mutual independence between reports of the four features (see Figure 1). For 5 out of the 8 observers, product–moment correlation coefficients between the observed and predicted probabilities were above .95; for 3 of the 5 observers, the agreement between observed and predicted probabilities was almost perfect, with correlations exceeding .99 (see Table 1).

For the remaining 3 of the 8 observers, the correlations between the observed and predicted probabilities across the 16 types of report were moderately high, but not perfect. The deviations between observed and predicted probabilities were highly systematic. Consider the cases in which just two features are correctly reported (Report Types 6–11). Report Types 6 and 7 cover the cases in which the two features belong to the same letter. Without exception, these cases were more frequent than predicted by assuming mutual independence between reports of the four features (see data for Observers S6–S8 in Figure 1). Report Types 8–11 cover the cases in which the two features belong to different letters. Without exception, these cases were less frequent than predicted.

Although Observers S6–S8 gave fewer reports of Types 8–11 than predicted by assuming mutual independence between reports of the four features, the observed probability of a report of one of these types (a report containing just one feature from each of the two stimuli) was substantial (.13–.15) in each of the 3 observers. Across all of the 8 observers, the proportion of reports of Types 8–11 ranged from .08 to .32, with a median of .15.

False Reports

The observed probability of false report of a given feature (i.e., the proportion of trials in which the feature was erroneously reported) is shown in Table 3 for each observer and each of the four features. Averaged across locations and observers, the percentages of false reports among all reports were 17% for shape reports and 30% for color reports. The observed probability that the shape of a letter was omitted from a report averaged .10, and the probability that the color of a letter was omitted from a report averaged .18.

Although the number of false reports was substantial (especially for color reports), cases in which presented colors or shapes were mislocalized (*illusory conjunctions* of color or shape with location; Treisman, 1988) were rare. In the terminology proposed by Sperling and Speelman (1970), the analyses we have reported so far were based on *position scores* (numbers of features reported correctly with respect to both their identities and their locations). Let the *feature score* with respect to color or shape be the position score that would be obtained if, before scoring, the locations of the colors or shapes, respec-

Table 2
Possible Types of Report

Type	Left Shape	Left Color	Right Shape	Right Color
1	0	0	0	0
2	1	0	0	0
3	0	1	0	0
4	0	0	1	0
5	0	0	0	1
6	1	1	0	0
7	0	0	1	1
8	1	0	1	0
9	0	1	0	1
10	1	0	0	1
11	0	1	1	0
12	1	1	1	0
13	1	1	0	1
14	1	0	1	1
15	0	1	1	1
16	1	1	1	1

Note—Entries of 1 and 0 indicate correctly and not correctly reported features, respectively.

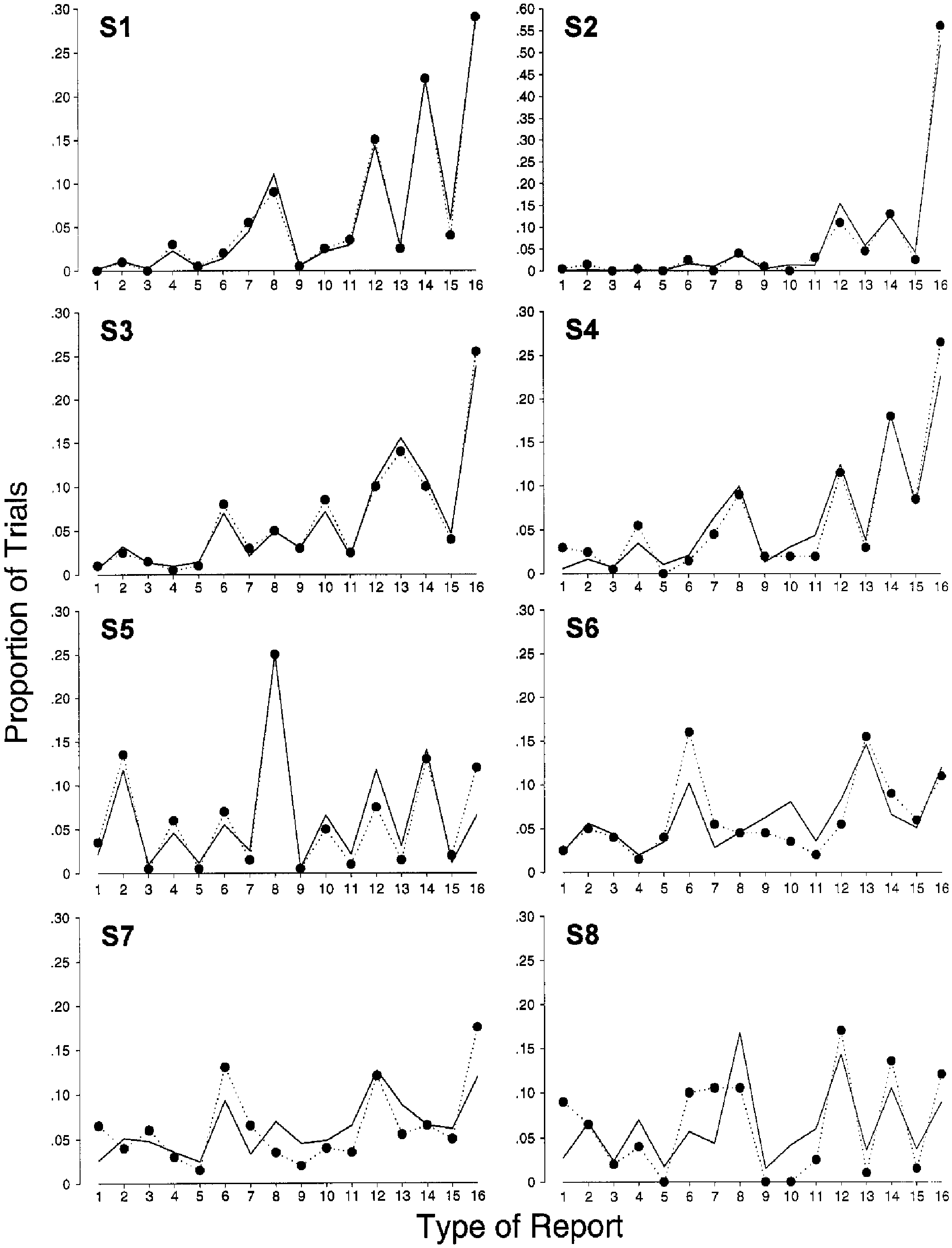

Figure 1. Observed and predicted probability distributions of reports of pairs of colored shapes across 16 types of report for Observers S1–S8. Observed probabilities are shown by solid circles connected with dotted lines. Predicted probabilities are indicated by unmarked points connected with unbroken lines. The predictions were derived from observed probabilities (in Table 1) of correct identification of the left shape, the left color, the right shape, and the right color, respectively, by assuming mutual independence between reports of the four features. The 16 types of report are defined in Table 2.

tively, were permuted so as to maximize the position score. Mislocalizations of presented colors or shapes should make the feature scores higher than the position scores. However, differences between feature and position scores were small. Averaged across observers, the position scores were 1.49 shapes and 1.16 colors per trial (cf. Table 1). The corresponding feature scores were 1.50 shapes and 1.21 colors per trial.

Table 3
Observed Probabilities of False Report

Observer	Left Shape	Left Color	Right Shape	Right Color
S1	.12	.25	.06	.25
S2	.07	.12	.03	.14
S3	.15	.32	.38	.28
S4	.24	.26	.13	.25
S5	.13	.42	.28	.35
S6	.04	.09	.07	.06
S7	.32	.29	.30	.23
S8	.11	.33	.07	.33
M	.15	.26	.16	.23

Note—The observed probabilities in the table are the proportions of trials with false reports for each of the four features (two colors and two shapes) of a pair of colored letters, one to the left and one to the right of fixation.

DISCUSSION

Our main result is the clear evidence in several observers of nearly perfect stochastic independence between encoding of each of the four features (two colors and two shapes) of a briefly presented pair of colored letters. For 5 out of the 8 observers, the observed probabilities of all possible combinations of correctly and not correctly reported features agreed very closely with the predictions obtained by assuming perfect independence between reports of the four features (see Figure 1). Such stochastic independence is readily explained by many parallel-processing models. For example, in the theory of visual attention (TVA) proposed by Bundesen (1990, 1991, 1998), encoding processes for colors and shapes are stochastically independent both within and between stimulus items when the number of items is less than the span of apprehension (at four items plus or minus one) and the attentional set is kept constant across trials.

Observers S6–S8 showed systematic deviations from the predictions made by assuming independence between the reports of each of the four features (two colors and two shapes). For these observers, reports of both features from one of the stimuli and no features from the other one (Report Types 6 and 7) were more frequent than predicted by the independence assumption, whereas reports of just one feature from each of the stimuli (Report Types 8–11) were less frequent than predicted (see Figure 1). These deviations from stochastic independence are exactly as predicted by TVA if we assume that Observers S6–S8 were unable to keep the attentional weighting of the stimulus letters completely constant from trial to trial. Any variation in the attentional weighting of the stimulus letters across trials with comparatively greater weight on the left-hand letter in some trials and comparatively greater weight on the right-hand letter in other trials should induce a positive correlation between encoding of color and encoding of shape from the same stimulus and a negative correlation between encoding of features from one of the stimuli and encoding of features from the other one (cf. Bundesen, 1990, p. 528; Monheit & Johnston, 1994). Thus, a parallel-processing model such as TVA can explain both (1) the close agreement for Observers S1–S5 between observations and predictions based on independence and (2) the systematic deviations for Observers S6–S8 between observations and predictions by independence.

In contrast, our results are difficult to reconcile with plausible serial models of processing. Consider a simple serial model in which the stimulus letters are processed one by one so that the encoding of one of the stimuli in a pair is completed before the encoding of the other one is begun (see Bundesen, 1996; Townsend & Ashby, 1983; Treisman, 1988). In this model, there should be no trials in which subjects encode just one feature from one of the stimuli and one feature from the other one. Reports containing just one feature from each of the two stimuli might occur if the encoding of a feature was in error, an encoded feature was forgotten, or a guess was made, but such events would be expected to be rare. However, our data showed that all observers gave many reports containing just one feature from each of the two stimuli: both shapes (Report Type 8), both colors (Report Type 9), or even the color of one of the stimuli and the shape of the other one (Report Types 10 and 11). The high frequency of such reports speaks against the serial model. Prima facie, the high frequency of reports containing just one feature from each of the two stimuli suggests that the stimuli were processed concurrently in the sense that encoding of both stimuli was commenced before encoding of either stimulus had been completed.

Could any serial model predict the pattern of results found for Observers S1–S5? To predict stochastic independence between the four features (two colors and two shapes) of the stimulus pairs, a serial model could assume that on every trial, the observer devoted exactly t_L msec to processing of the left stimulus and t_R msec to processing of the right stimulus. For example, if attention was initially directed to the left stimulus and shifted to the right stimulus after t_L msec, regardless of whether and when the observer had identified any features of the left stimulus, then stochastic independence between the four features would be expected. But if the time t_L spent on the left stimulus showed any random variation from trial to trial, this variation should induce a positive dependence between the two features of the left stimulus. Furthermore, if the time t_R spent on the right stimulus varied inversely with t_L (e.g., t_R could equal the total time available for processing minus t_L), then the variation in t_L should also induce positive dependence between the two features of the right stimulus and negative dependence between features from different stimuli. Thus, it seems impossible to explain the pattern of results found for Observers S1–S5 by any plausible serial model.

Related Findings

Standard whole-report paradigm. Our experimental technique combines a standard whole-report procedure (e.g., Sperling, 1960) with procedures for investigating dependencies between processing of different feature dimensions (e.g., Nissen, 1985). Several previous whole-report experiments have provided evidence of mutual independence between reports of each of a small number of simultaneously presented alphanumeric characters (see Busey & Townsend, 2001, for a thorough analysis of an exception). For example, Eriksen and Lappin (1967) found mutual independence between reports of two, three, or four simultaneously presented letters. Townsend (1981) found mutual independence between reports of individual letters in five-letter strings. Shibuya and Bundesen (1988) found evidence of mutual independence between reports of individual items for displays within the subject's span of apprehension (at four items plus or minus one). For display sizes beyond the span of apprehension, reports of individual items have shown negative dependencies (see, e.g., Shibuya, 1993, p. 721).

Nissen's partial-report paradigm. Other studies have addressed encoding of multiple features from a single stimulus. For example, in partial report of a colored (geometric) shape that was cued by its location in a four-element array (by a location cue presented simultaneously with a pattern mask at the offset of the display), Nissen (1985) found evidence of stochastic independence between reports of color and shape: The probability of reporting both features of the cued element correctly was approximately the same as the product of the probability of reporting the color correctly and the probability of reporting the shape correctly. Isenberg, Nissen, and Marchak (1990) replicated this finding with four-element arrays of bars in different colors and orientations.

In a more extensive investigation of performance in Nissen's (1985) paradigm with both four- and six-element arrays of colored shapes (letters), Monheit and Johnston (1994) found significant positive dependence between reports of color and reports of shape (see also the reply by Johnston, Ruthruff, & Monheit, 1997, to the commentary by van der Velde & van der Heijden, 1997). The positive dependence was stronger for six-element displays but very clear for both display sizes. The dependence appeared, in part, as consistent location advantages. For example, for displays with four letters that appeared above, below, to the left, and to the right of the fixation point, accuracies of color and shape reports covaried strongly across locations so that both color and shape were reported much more accurately when the cued element was the letter to the right of the fixation point rather than the letter below the fixation point. Thus, trial-to-trial variation of the location of the cued element was a major cause of the positive dependence found between reports of color and shape (see Monheit & Johnston, 1994, p. 702). Another likely cause of the positive dependence was variation in the efficiency with which the location cue (a central arrow pointing to one of the target positions) was processed. Any random variation from trial to trial in the efficiency of cue interpretation should induce a positive correlation between report of the color of the cued element and report of the shape of the cued element. This analysis suggests that the clear positive dependencies between reports of color and shape in the experiments by Monheit and Johnston were due to their use of a partial-report procedure (with post-stimulus cuing).

Conclusion. Results from standard whole-report studies and studies using the partial-report paradigm of Nissen (1985) seem generally consistent with the results reported in this article. The results suggest that, when the number of stimulus items is less than the span of apprehension (at four items plus or minus one), and the attentional set is kept constant across trials, encoding processes for colors and shapes are stochastically independent both within and between items. Such stochastic independence is predicted by many parallel-processing models (e.g., Bundesen, 1990; Palmer et al., 2000). However, the results are difficult to reconcile with simple serial models in which the encoding of one object (with all its relevant features) is completed before the encoding of another object is begun.

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