PERCEPTUAL ASYMMETRY AND MEMORY RETRIEVAL IN 3-MONTH-OLD INFANTS

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In visual search tasks with adults, the presence of a feature is detected more rapidly than its absence. In two experiments, we asked if perceptual asymmetry affects the detection of effective retrieval cues. Three-month-olds learned to kick to move a mobile displaying either Rs (feature present) or Ps (feature absent), and these same stimuli were used later as retrieval cues during a long-term retention test. In Experiment 1, infants were tested after 24 hrs with a single P amidst six Rs or vice versa. In concordance with feature integration theory (Treisman, 1986), the feature-present target popped out while the feature-absent target did not. In Experiments 2A-2B, infants were tested after 24 hrs with novel homogeneous mobiles. Although the R mobile was not an effective retrieval cue for P-trained infants, the P mobile was an effective retrieval cue for R-trained infants. Even after only 1 hr, infants failed to discriminate the P test mobile from the R training mobile indicating that they had forgotten the tail of the R as rapidly as this short delay. These findings reveal that perceptual asymmetry alone does not completely determine retrieval from long-term memory. Rather, whether the detail that differentiates the feature-present stimulus from the feature-absent stimulus is accessible to working memory needs to be considered.

perceptual asymmetry **visual pop-out** **memory retrieval** **working memory** **attention**

Recent adult and infant studies of visual information processing have found asymmetries in the detection of objects that are defined by either the presence or absence of a particular attribute. Williams and Julesz (1992), for example, reported that adults detected a field of open circles (C) embedded in a field of closed circles (O) more readily and accurately than they detected a field of closed circles embedded in a field of open ones. Presumably,

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the presence of gaps and line terminators in the open circles, which were absent in the surrounding field of closed circles, increased their discriminability when they were the target (also see Julesz, 1981). Beck (1973) and Gurnsey and Browse (1987) demonstrated a similar asymmetry in the ease of texture segregation, depending on whether the micropattern elements that contained the additional critical feature formed the foreground or the background. In visual search paradigms, adults also detect a stimulus with an additional critical feature faster than a stimulus in which that feature is absent (Treisman & Gormican, 1988; Treisman & Souther, 1985). Thus, a Q that is embedded in a field of Os (feature-present condition) is noticed immediately, and the time to detect the Q is unaffected by the number of distractors (Os) in which it is embedded. In contrast, an O in a field of Qs (feature-absent condition) is more difficult to detect, and the time required to find it increases linearly with the number of distractors (Qs).

Search asymmetries have also been reported in the animal literature. Allan and Blough (1989), for example, presented pigeons with either a target triangle that contained a gap surrounded by distractors that were closed figures or a target triangle that was closed surrounded by distractors that contained a gap. They found that the closed target popped out irrespective of the number of distractors, while the target with a gap did not.[1] Similarly, animals can be trained to approach a stimulus that possesses a critical feature more easily than one that lacks it (Jenkins & Sainsbury, 1970). The latter is known as the "feature-positive" effect.

The asymmetry in the ease of detecting stimuli defined by the presence versus the absence of a feature is consistent with Treisman's feature-integration theory of object recognition (Treisman & Gelade, 1980), which proposes that two different subsystems control visual information processing. In the early stage, the preattentive system decomposes a visual pattern via a parallel search process in which critical features of objects "pop-out" or call attention to themselves (Treisman, 1988). These perceptual primitives, which include line orientation, curvature, tilt, closure, color, and spatial frequency, are described as the building blocks of perception and are hypothesized to be coded on individualized feature maps. If a particular feature is present, then it activates a node on its map, enabling its immediate and automatic perception. If a critical feature is not present, however, no node on any feature map is activated; rather, an object defined by the absence of a feature can be detected only by an effortful serial search conducted by a later-acting, focused-attention system that enables object identification or recognition (Treisman & Souther, 1985).

Recently, attentional asymmetry has been observed in infants. Using a preferential-looking paradigm, Colombo, Ryther, Frick, and Gifford (1995) exposed 3- to 4-month-olds simultaneously to a homogeneous display composed entirely of Os or Qs and a heterogeneous display composed either of Os with a single discrepant Q (feature-present target) or Qs with a single discrepant O (feature-absent target). The percentage of looking time allocated to the heterogeneous array containing the feature-present target was significantly greater than chance, but the percentage of looking time allocated to the heterogeneous array containing the feature-absent target was not. This asymmetry in looking behavior suggested that the unique feature-present element popped out and captured infants' attention, but the unique feature-absent element did not. Colombo et al. (1995) concluded that attentional asymmetry is not the exclusive domain of mature perceptual systems but is characteristic of young infants' perceptual systems as well.

Taken together, the preceding examples suggest that visual feature-present/feature-absent asymmetry may be ubiquitous across phylogeny and ontogeny. Surprisingly, however, the functional significance of this phenomenon has yet to be examined. This neglect is particularly surprising considering that the early stage of information processing, which is thought to be accessed during visual search tasks (e.g., Cave & Wolfe, 1990; Treisman, 1988) and texture segregation tasks (e.g., Caelli, 1985; Julesz, 1975), is thought to be the precursor to the later processing stage, which permits object identification or recognition (i.e., memory retrieval) if the detected object strikes a match with the contents of long-term memory. Support for the sequential nature of these information-processing stages comes from evidence that the recognition and identification of an object is influenced by the ability to detect and discriminate the object from its surround (Bergen, 1991). The time to discriminate embedded targets from surrounding items, for example, is speeded both by practice (Ahissar & Hochstein, 1995; Karni & Sagi, 1991) and by arranging the targets in a recognizable configuration such as a face (Gorea & Julesz, 1990). This evidence suggests that asymmetries in the detection of feature-present versus feature-absent stimuli might produce corresponding effects in memory performance if feature presence or absence were to characterize potential retrieval cues.

In the succeeding experiments, our goal was to explore the potential functional relationship between feature presence/absence and the retrieval of previously encoded information from long-term memory. Our study population, 3-month-old infants, was considered to be ideal for assessing potential perceptual asymmetry effects on recognition because retention at this age is very strongly determined by the perceptual similarity between the features present during training (encoding) and testing (retrieval). We have argued elsewhere that primitive perceptual features may actually be the data base on which the young infant's memory processes operate (Adler & Rovee-Collier, 1994; Bhatt, Rovee-Collier, & Weiner, 1994; Rovee-Collier, Hankins, & Bhatt, 1992). In Experiment 1, we tested infants' 24-hr recognition with a heterogeneous pop-out display in which the unique target stimulus was characterized by either the presence or absence of a feature relative to the concurrently surrounding distractors. In Experiment 2A, we tested infants' 24-hr recognition with a homogeneous novel display that contained either the presence or absence of a feature. During testing, infants produced a motoric "yes" (kick rate above baseline) if they recognized the test display and a motoric "no" (kick rate not above baseline) if they did not. This test procedure is analogous to yes/no recognition tests that are used in studies of adult recognition (e.g., Tversky & Tuchen, 1989).

EXPERIMENT 1: 24-HR RETENTION TEST WITH A POP-OUT DISPLAY

In adult studies, a visual pop-out paradigm is typically used to test detection of a perceptual feature. In this paradigm, a single unique item (or patch) is presented among multiple dissimilar distractors, and detection is thought to result from a parallel search of the visual field (preattentive-processing). An item possessing a highly distinctive feature is typically detected immediately and automatically, but an item lacking that feature is not (Neisser, 1963; Treisman, 1985; Treisman & Souther, 1985). Presumably, the added feature captures attention and stands out from the background of distractors in the display (Treisman, 1988). Pop-out displays have been used to examine the capacity of infants aged 3 months and older for texture segregation (Atkinson & Braddick, 1992; Rieth & Sireteanu, 1994; Sireteanu & Rieth, 1992). These studies have indicated that embedded textures that differ in orientation or size from surrounding textures pop out and are segregated by young infants, but they have failed to yield reliable evidence of feature discrimination by infants younger than 10 months of age. Recently, however, Colombo et al. (1995) found that 3- to 4-month-old infants fixated a discrepant display containing a single feature-present target at a level greater than chance than a simultaneously presented homogeneous array but fixation of a feature-absent display, however, was not above chance. They concluded that the feature-present target popped out while the feature-absent target did not, suggesting that infants manifest visual pop-out and asymmetry in feature detection similar to that displayed by adults.

Evidence of visual pop-out at 3 months has also been reported in studies of long-term memory involving mobile conjugate reinforcement. In this work, a unique item among homogeneous distractors captured attention not only during original encoding (Adler, Gerhardstein, & Rovee-Collier, 1998) but also in a delayed-recognition paradigm 24 hrs later and in a reactivation paradigm 2 weeks later (Rovee-Collier et al., 1992). In addition, whether or not the unique item popped out was independent of the number of distractors in which it was embedded (Rovee-Collier, Bhatt, & Chazin, 1996). In all of these studies, when the unique test target was novel and the distractors were familiar training stimuli, infants treated the entire mobile as if it were novel and failed to recognize it during the long-term retention test, despite the overwhelming number of familiar distractors on the test mobile. Conversely, when the unique test target was the one with which infants had been trained and the distractors were novel, they behaved as if the entire test mobile were composed of training stimuli and displayed excellent recognition during the long-term test, despite the overwhelming number of novel distractors on the test mobile. These studies demonstrated that infants could detect a familiar item (i.e., a retrieval cue) if it popped out from a large display of novel items, but they could not detect the very same item—even if it was present in a much greater number—if a single novel cue popped out instead. Whether an effective retrieval cue or a novel cue pops out from a test display, therefore, will determine whether or not infants exhibit long-term retention, respectively.

In the first experiment, we asked whether the presence or absence of a critical feature affects whether or not, respectively, a retrieval cue pops out. The work by Colombo et al. (1995) suggested that it might. To answer this, we trained infants with a mobile composed of blocks displaying either Rs or Ps and tested their recognition 24 hrs later with one of two mobiles: a mobile containing either a single R (feature-present condition) or a single P (feature-absent condition) block embedded amidst six novel blocks (P or R, respectively), or a mobile containing a single novel block embedded amidst six training blocks. We predicted that infants would detect an R among Ps but not a P among Rs, irrespective of whether the unique item was the training character or was the novel one. If the unique item did not pop out, then infants' recognition performance would be determined by the nature of the distractors, that is, whether they are familiar or novel.

Method

Participants

Thirty-two healthy, full-term 3-month-old infants (15 males, 17 females) were recruited from published birth announcements in local newspapers and by word of mouth. Their ages ranged from 80 to 114 days ($M = 98.4$ days, SD = 9.4) on the first day of training. Infants were randomly assigned to four experimental groups ($n = 8$) as they became available for study. Additional infants were excluded as a result of crying ($n = 8$) or inattention to the mobile ($n = 4$) longer than 2 consecutive minutes in any of the three sessions, or for failing to meet the initial learning criterion (a response rate 1.5 times above operant level during 2 of any 3 consecutive minutes of an acquisition phase; $n = 2$). This level of attrition is consistent with that of previous multiple-session studies in which infants have an opportunity to be lost from the final sample on each of several occasions (e.g., Greco, Hayne, & Rovee-Collier, 1990; Hayne, Rovee-Collier, & Perris, 1987).

Apparatus

Infants were trained with one of two mobiles composed of seven pink wooden blocks (3.2 cm^2), each side (including the bottom of the block) of which displayed computer-generated black lines that were arranged as either Ps or Rs. When stationary, the range of subtended visual angle for the blocks on the mobile was approximately 5.2° to 7.0°, while the range of subtended visual angle for the width of the black lines that made up the stimuli was approximately 2.5° to 3.5°. The stimuli differed only in the presence or absence of a single stimulus feature—the diagonal line that differentiates an R from a P. Notice that the P stimulus, in addition to missing one feature (i.e., the horizontal line), is also a perceptual subset of the R stimulus. That is, all of the featural components of the P are contained within the R. Twenty-four hours after training, infants were tested with a mobile identical to one of the training mobiles except that a single, unique block was substituted into the central position of the seven-block array (see Figure 1a & b).

During each session, the mobile was suspended from an overhanging, inverted L-shaped metal stand (BCS, So. Plainfield, NJ) that was clamped to a crib rail such that the mobile hung 25 to 30 cm above the infant's abdomen. A second stand was clamped to the opposite crib rail. One end of a soft, white-satin ribbon was connected without slack to the infant's ankle closest to the experimenter, while the other end was attached to one of the mobile stands. During reinforcement phases, the ribbon was connected to the same stand from which the mobile was suspended such that infants' kicks

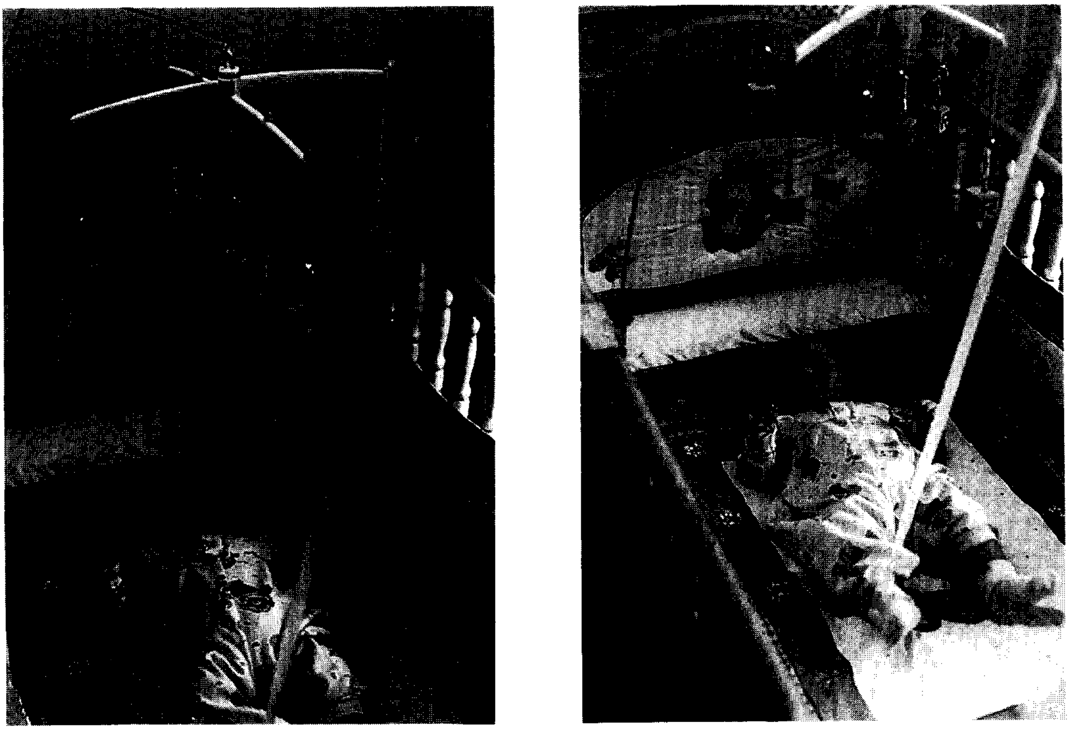
(a) (b)

FIGURE 1
The pop-out test stimuli used in Experiment 1. (a) A feature-present pop-out display, consisting of a unique R block (the target) amidst six P blocks (the distractors). (b) A feature-absent pop-out display, consisting of a unique P block (the target) amidst six R blocks (the distractors).

could activate it (i.e., each block bounced and swung independently). During nonreinforcement phases, the ribbon was connected to the "empty" stand. In this arrangement, infants could see the mobile, but kicks could not move it.

All groups were trained for 2 consecutive days with a mobile displaying either Ps or Rs and were tested 24 hrs later with a pop-out mobile which displayed a single unique P or R amidst either Rs or Ps, respectively. *Group R/P(R)*, a familiar, feature-present pop-out test group, was trained for 2 days with seven R blocks and was tested with six novel P blocks and one familiar R block. *Group P/R(P)*, a familiar, feature-absent pop-out test group, was trained with seven P blocks and was tested with six novel R blocks and one familiar P block. *Group P/P(R)*, a novel, feature-present pop-out test group, was trained with seven P blocks and was tested with six familiar P blocks and one novel R block. *Group R/R(P)*, a novel, feature-absent pop-out test group, was trained with seven R blocks and was tested with six familiar R blocks and one novel P block. (In the group labels, the first character represents the characters on the training mobile, the character after the slash represents the distractors on the test mobile, and the parentheses contain the unique or "pop-out" character on the test mobile.)

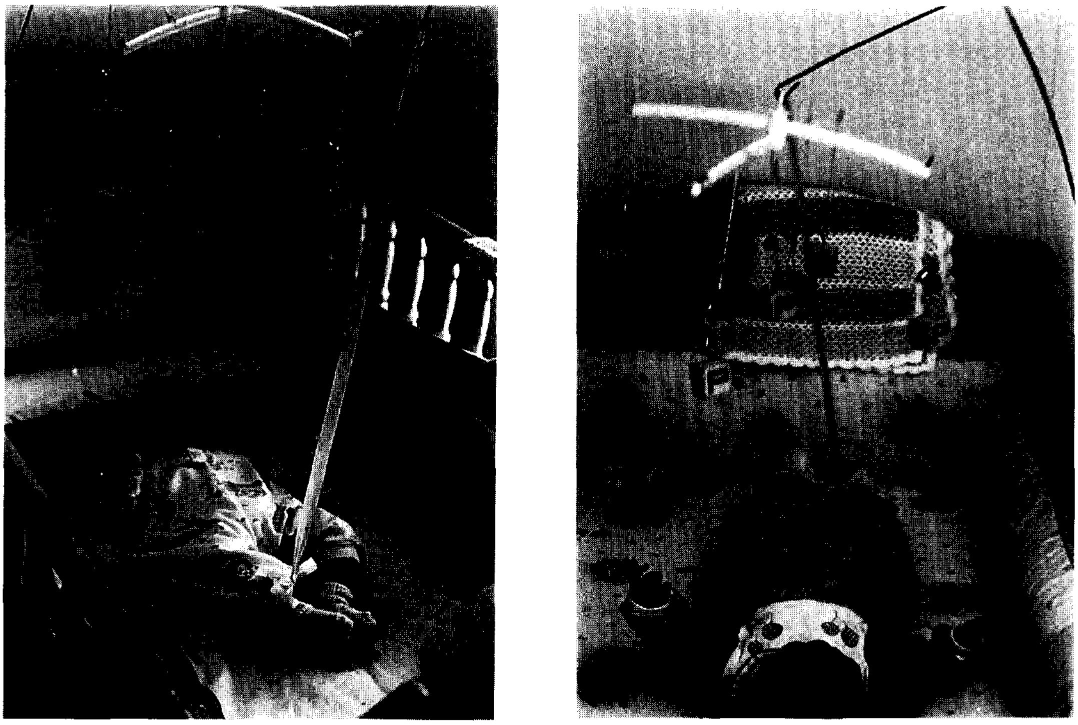
(a) (b)

FIGURE 2
(a). The experimental arrangement used during nonreinforcement phases (baseline, retention tests); the ankle ribbon was connected to the empty mobile stand, and kicks could not activate the mobile; shown here with feature-present stimuli (R blocks). (b). The experimental arrangement used during reinforcement phases (acquisition); the ankle ribbon was attached to the mobile stand, and kicks could activate the mobile; shown here with feature-absent stimuli (P blocks)

Procedure

All infants were trained and tested in their home cribs during an alert/play period designated by the infant's mother. This time varied from infant to infant but remained relatively constant for a given infant. Each infant received two 15-min training sessions on 2 consecutive days and a test session 24 hrs later. Each session began and ended with a 3-min nonreinforcement period during which the ribbon was attached to one mobile stand, and the mobile hung from the other (see Figure 2a). In this arrangement, the mobile remained stationary despite the infant's kicks. The initial 3 min of Session 1 was a *baseline phase* during which the infant's unlearned kick rate (kicks/minute) or operant level was measured. The next 9 min was a reinforcement phase (*acquisition*) during which the ankle ribbon was attached to the same stand as the mobile (see Figure 2b). In this arrangement, the infant's kicks activated the mobile in proportion to the rate and intensity of responding ("conjugate reinforcement"). Finally each session ended as it began, with a 3-min nonreinforcement phase during which the ankle ribbon was returned to the inactive stand.

The last 3 min of Session 2 was the *immediate retention test* (IRT) phase, when the infant's final learning level (kicks/minute) was assessed after zero delay. The first 3 min of Session 3 was the *long-term retention test* (LTRT) phase, when the infant's response rate (kicks/minute) was assessed after a 24-hr delay. We emphasize that retention was measured only during periods when the stationary mobile and the ankle ribbon were attached to different stands. In this way, measures of retention reflected only what the infant brought into the session from his/her prior training experience and not new learning or savings at the time of testing. Reacquisition and re-extinction phases were introduced immediately after the long-term retention test to ensure that infants who had not responded during the test were not unmotivated or sick. None were.

A trained observer, positioned out of the infant's line-of-sight, recorded the number of kicks per minute of the foot with the ankle ribbon. A kick was defined as a horizontal or vertical movement of the foot that at least partly retraced its original arc of excursion in a smooth, continuous motion (Rovee & Rovee, 1969). Only infants who met the original learning criterion were retained for retention testing in the third session. A second observer, naive with respect to the hypothesis and an infant's session number, independently recorded kicks/minute for 102 min during seven randomly selected sessions of five infants across all experiments. A Pearson product-moment correlation between their joint response counts/minute yielded an interobserver reliability coefficient of 0.91.

RESULTS AND DISCUSSION

Retention was analyzed in terms of two individual measures of relative responding (baseline ratio, retention ratio) that we have used in all previous studies of infant memory (for review, see Rovee-Collier & Hayne, 1987). The primary measure, the *baseline ratio*, was computed by dividing an infant's mean response rate during the long-term retention test (i.e., the first 3 min of nonreinforcement of Session 3) by that same infant's mean baseline rate (i.e., the first 3 min of nonreinforcement of Session 1). The resulting proportion indicates the extent by which responding during the long-term retention test exceeds operant level. If a group's mean baseline ratio is significantly greater than a theoretical population baseline ratio of 1.00, then the group exhibited significant recognition. If the mean baseline ratio does not significantly exceed 1.00, then the group exhibited a retrieval deficit, performing during the long-term test at a level equivalent to their pretraining baseline rate. Thus, the significance level of the baseline ratio indicates an all or none effect—significant mean baseline ratios indicate retention while nonsignificant mean baseline ratios indicate retention failure. Beyond that, the value of the mean baseline ratio does not indicate the degree of retention.

The second measure, the *retention ratio*, was calculated by expressing an infant's mean response rate during the long-term retention test as a fraction of that same infant's mean response rate during the immediate retention test (i.e., the last 3 min of nonreinforcement of Session 2). This measure indicates the degree of infant's long-term retention relative to his/her retention after zero delay. A group mean retention ratio equal to or greater than 1.00 indicates that responding was as great during the long-term test as it was during the immediate test. A mean group retention ratio significantly less than a theoretical population retention ratio of 1.00 indicates a significant decrement in that group's performance during the long-term test. After a 1-day test delay, this would indicate that infants detected a change in the mobile display from training to testing. A group's retention ratio is informative about the degree of decrement, however, only if it exhibited significant retention (mean baseline ratio significantly > 1.00) in the first place.

To insure that differences in test performance were not due to differences in either initial activity levels or final levels of acquisition, separate unweighted means one-way analyses of variance (ANOVAs) were performed over the mean kicks of the four independent groups during the baseline phase and the immediate retention test. These analyses indicated that the groups did not significantly differ either prior to training, $F(3, 28) = 0.16$, *ns*, or immediately following it, $F(3, 28) = 0.24$, *ns*, respectively. Thus, different levels of conditioning to the training stimuli could not account for whether or not a group exhibited pop-out.[2]

Group mean baseline and retention ratios are presented in Table 1. Identical one-way ANOVAs over the mean baseline ratios, $F(3, 28) = 0.15$, *ns*, and mean retention ratios, $F(3, 28) = 1.00$, *ns*, of the four groups also yielded no significant differences. Although ANOVAs reveal whether or not groups differ from one another, they do not answer our primary question of interest, that is, whether or not any given group exhibited retention. All may have, for example, or none may have. To answer this question, we used directional t tests to compare each group's mean baseline and retention ratios with the corresponding theoretical population ratios of 1.00 (no retention and no retention deficit, respectively).

These tests revealed that three of the four groups exhibited significant recognition. As was expected for the familiar feature-present pop-out test condition, *group R/P(R)* had a mean baseline ratio significantly above a theoretical baseline ratio of 1.00, $t(7) = 3.84$, $p < .004$, indicating that the familiar R target cap-

TABLE 1
Mean baseline (BR) and retention (RR) ratios, *SEs*, *ts*, and *p* values for four test groups ($n = 8$) of 3-month-olds as a function of the familiarity (FAM) or novelty (NOV) and of feature presence vs. feature absence of the pop-out target in Experiment 1

Group	*FAM or NOV*	*BR*	*SE*	t^a	*p*	*RR*	*SE*	t^b	*p*	*Pop-Out?*
				Feature-Present Target						
R/P(R)	FAM	1.48	0.13	3.84	0.004	0.65	0.12	2.84	0.02	Yes
P/P(R)	NOV	1.66	.036	1.86	n.s.	0.88	0.23	0.50	n.s.	Yes
				Feature-Absent Target						
P/R(P)	FAM	1.36	0.21	1.75	n.s.	0.61	0.08	5.15	0.001	No
R/R(P)	NOV	1.42	0.14	2.96	0.02	0.57	0.06	7.66	0.0001	No

[a] Comparison with a theoretical baseline ratio of 1.00 (i.e., no retention).
[b] Comparison with a theoretical retention ratio of 1.00 (i.e., no retention deficit).

tured infants' attention and controlled their retention. Interestingly, this group had a mean retention ratio that was significantly less than 1.00, $t(7) = 2.84$, $p < .015$, suggesting that their retention, while significant, was impaired by the novel distractors in which the effective retrieval cue was embedded. In contrast, *group P/P(R)*, for whom the feature-present test target was novel, exhibited no evidence of retention, indicating that the R again popped out and determined test performance, despite the overwhelming number of familiar P distractors. The mean baseline ratio of this group was not significantly above 1.00, $t(7) = 1.86$, *ns*, and its mean retention ratio was not significantly different than 1.00. The relatively large variability in this group's mean baseline ratio was due to a single infant's baseline ratio being unusually low.

As predicted by the search-asymmetry hypothesis, *group R/R(P)*—whose novel test target lacked the critical feature—also had a mean baseline ratio significantly above 1.00, $t(7) = 2.96$, $p < .015$. Because the retention failure of infants in *group P/P(R)* was due to the single novel target even though the same number of familiar items was present in their test display, we conclude that infants' exhibited retention, in contrast, was not due to pop out of the single novel P target but was instead determined by attention to the familiar distractors (Rs), which were effective retrieval cues. That is, in order for these infants to display recognition, their attention must have been localized on the familiar R distractors which also happened to possess the critical feature. The mean retention ratio of this group, however, was significantly less than 1.00, suggesting that some attention was allocated to the feature-absent P target and by virtue of being novel yielded only partial retention. In contrast, when the feature-absent test target was familiar (*group P/R(P)*), the mean baseline ratio was not significantly above 1.00, $t(7) = 1.36$, *ns*, and the mean retention ratio was significantly less than 1.00, indicating that the P target did not pop out and retrieval was precluded by novel feature-present R distractors. Note that the relatively large variability in this group's mean baseline ratio, in contrast to *group P/P(R)*, was due to a single infant's baseline ratio being unusually high.

These data are consistent with findings from studies of visual search with adults (Treisman & Gormican, 1988; Treisman & Souther, 1985) and infants (Colombo et al., 1995) in which a unique feature-present target pops out and captures attention, but a unique feature-absent cue does not. Restated, a unique target stimulus that *possessed* an additional critical feature (feature-present conditions) popped out of both test displays, producing recognition if it was familiar and none if it was novel. Also as predicted, a unique target stimulus that lacked the critical feature (feature-absent conditions) failed to pop out from the test display and recognition was consequently determined by whether the feature-present distractors were familiar or novel.

These results suggest that perceptual asymmetry facilitates memory retrieval in two ways: (a) by enhancing attention to a unique feature-present target in a pop-out test display whether it is novel or familiar, and (b) by diminishing attention to a novel feature-absent target relative to familiar feature-present distractors. Thus, in all cases, memory retrieval is determined by differential attention in favor of feature-present stimuli in the array, whether they are the target or the distractors. When the feature-present stimuli are novel (i.e., *groups P/P(R)* and *P/R(P)*), their command of the attentional resources produces a negative effect on memory retrieval, yielding a retention failure. On the other hand, attention to familiar feature-present stimuli predictably manifests a significant memory retrieval, but its efficacy is surprisingly impaired, however, presumably as a consequence of at least partial attention to the novel feature-absent items in the array.

An account of the results may be derived from the fact that there are two stimulus characteristics that can control infants attention: feature-presence and novelty. Attentional capture has been shown, in both adults (Treisman

& Gormican, 1988; Treisman & Souther, 1985) and infants (Colombo et al., 1995), to be controlled by the early perceptual processing of the presence of a unique feature. In infants, visual attention has also been extensively shown to be quite sensitive at test to novel stimuli after an initial familiarization period with a different stimulus (e.g., Cohen & Gelber, 1975; Fagan, 1977; Fantz, 1964). The present results suggest that these two stimulus characteristics have hierarchical roles in the control of infants' attention and, consequently, the exhibited memory performance. Initial attention seems to be controlled by the early perceptual processing or pop-out of the presence of a feature, as evidenced by the R stimulus in the pop-out display determining whether retention or retention failure was exhibited regardless of whether it was the target or the distractors. Subsequently, attention is also allocated to the novel stimulus in the display; thus, the exhibition of retention when the initially attended R stimulus was familiar was impaired by subsequent attention to the novel P stimulus, but retention failure results when the R stimulus was novel, despite the presence of the familiar P cues, because initial and subsequent attention is allocated to it. If this account is correct, then testing with a display, in which familiar feature-present Rs are not available to initially capture attention and cue memory retrieval, but which contains only novel Ps, should completely impair memory retrieval. This prediction was tested in Experiment 2A by training infants with Rs and then testing them 24 hrs later with a homogeneous display of novel Ps.

EXPERIMENT 2A: 24-HOUR TEST WITH A NOVEL HOMOGENEOUS DISPLAY

The preceding experiment yielded support for the hypothesized search-asymmetry effect on memory performance. By this account, the unique feature-present target popped out and the feature-absent target failed to pop out. This perceptual asymmetry is held to be responsible for the corresponding asymmetry in recognition: Infants exhibited no retention when the feature-present cue was novel, but they exhibited significant retention when the feature-absent cue was novel—presumably via the capturing of attention by the familiar feature-present items, which were effective retrieval cues. This result suggests that novel stimuli that are not perceptually discriminable are also not mnemonically discriminable (cf. Adler & Rovee-Collier, 1994). The exhibited retention when the feature-absent cue was novel, however, was partially impaired, suggesting that after the initial capture of attention and memory retrieval by the feature-present characters, the novelty of the feature-absent cue garnered some secondary attention and was perceptually and mnemonically discriminated. If one tested with a homogeneous display of novel feature-absent items then attention should be focused on the novelty of these cues because feature-present items are not exhibited in the array and, therefore, are not able to control initial attentional allocation. As a result, infants would be expected to show complete retention failure because the feature-absent cues in the homogeneous display are novel.

At this point, it is important to recall that young infants' memories are coded in terms of highly specific features. What is noticed in the test display must strike a fairly veridical match with the representation in long-term memory or the training memory will not be retrieved, and the test display will not be recognized. Rovee-Collier et al. (1992), for example, found that infants who were trained with a mobile displaying black horizontal and vertical line segments arranged as +s discriminate a test mobile displaying black horizontal and vertical line segments arranged as Ls 24 hrs later, but infants trained with a mobile displaying Ts did not discriminate them from Ls a day later. Julesz (1981) argued that a + contains an additional primitive feature, a line crossing, which facilitates the discrimination of +s from Ls and Ts, which lack that feature. The findings of the preceding experiment with feature-present and feature-absent pop-out stimuli are reminiscent of those obtained by Julesz (1981, 1984) in adult studies of texture segregation in which the micropattern elements of the textures were Ts, Ls, and +s. That is, infants recognized the test display as long as it contained the same features that were present in the training display, but they failed to recognize the test display if it contained an additional feature. Infants' failure to discriminate between Ls and Ts suggests that infants may not discriminate Ps after being trained with Rs because all of the features in the Ps were present in the Rs.

The results of Experiment 1 suggested that a homogeneous display of feature-absent stimuli would be discriminated while the results of Rovee-Collier et al. (1992) suggested that they would not be discriminated. In Experiment 2A, therefore, we asked whether the feature-present versus feature-absent test conditions would yield an asymmetry in infants' 24-hr recognition of novel stimuli if the test display eliminated the potential contribution of familiar items as retrieval cues in the feature-absent condition. If novel feature-absent stimuli are not discriminated then, in the preceding study, the impairment of 24-hr retention displayed by infants in the novel feature-absent test groups (*groups R/R(P)* and R/P(R)) could not be solely attributed to subsequent attentional allocation to the novel feature-absent cue after initial attention to and memory retrieval by the familiar feature-present cues in the array. We accomplished this by using homogeneous test mobiles that displayed multiples of the same novel item (i.e., all Ps or all Rs for infants trained with Rs or Ps, respectively) that either possessed or lacked a critical feature. Because delayed object recognition in this test paradigm is highly sensitive to the details of the original training cue, we hypothesized that if infants did not notice the addition or deletion of the distinguishing segment on the test mobile (i.e., if they did not discriminate that the test and training displays differed), then they would respond to the test mobile as if it were their training mobile; if they did notice the addition or deletion, then they would not respond to the novel test mobile (i.e., it would not be an effective retrieval cue).

Method

Participants

Twenty-four 3-month-old infants (8 males, 16 females), recruited as before, were randomly assigned to three independent groups ($n = 8$) as they became available for testing. Their ages ranged from 74 to 112 days on the first day of training ($M = 97.0$ days, $SD = 8.9$). Additional participants were excluded from the final sample for crying for 2 consecutive minutes in any of the three sessions ($n = 7$), failing to reach the initial learning criterion ($n = 3$), or illness ($n = 1$).

Apparatus and Procedure

Infants were again trained with one of the two mobiles (P or R) that were used during training in Experiment 1. This time, however, they were tested with either the same mobile or the other one. In the feature-present test condition, infants were trained for 2 days with a P mobile and were tested 1 day later with an R mobile (*group P/R*); in the feature-absent test condition, infants were trained with an R mobile and were tested with a P mobile (*group R/P*). In the control test condition (*group no-change*), half of the infants were trained and tested with a P mobile, and half were trained and tested with an R mobile.

RESULTS AND DISCUSSION

To establish that the three groups did not differ either prior to or following training, separate unweighted means one-way ANOVAs were again performed over the mean kicks of the three groups during the baseline phase and the immediate retention test, respectively. These analyses yielded no significant differences among the groups, insuring that any subsequent group differences in retention were not due to differences in either unlearned activity, $F < 1$, or their final level of learning, $F(2, 21) = 0.87$, *ns*. Identical one-way ANOVAs yielded no significant differences between the mean baseline ratios of the three groups, $F(2, 21) = 1.50$, *ns*, but did reveal a significant difference in their mean retention ratios, $F(2, 21) = 3.93$, $p < .025$. A post-hoc test (Tukey-Kramer, $p = .05$) indicated that group P/R (the feature-present test group) had a significantly lower retention ratio than the no-change control group. The mean baseline and retention ratios are presented in Table 2.

As expected, a directional *t* test revealed that the no-change control group, which was tested with the original training display, showed near-perfect retention during the 24-hr test. Its mean baseline ratio was significantly above 1.00, $t(7) = 4.00$, $p < .003$, and its mean retention ratio was not significantly less than 1.00, $t(7) = 1.17$, *ns* *Group R/P* (the feature-absent condition) also exhibited excellent recognition. Like the control group, its mean baseline ratio was significantly greater than 1.00, $t(7) = 2.52$, $p < .02$, indicating that infants did not discriminate the test mobile which displayed a stimulus that lacked a feature from the training one. Its mean retention ratio, however, was significantly less than 1.00, $t(7) = 2.12$, $p < .04$, suggesting that retention was partial and although the P was an effective retrieval cue, infants did notice that it was novel. In contrast, *group P/R* (the feature-present test condition) treated the test mobile as novel during the 24-hr test. Its mean baseline ratio was not significantly above 1.00, $t(7) = 1.83$, *ns*, and its mean retention ratio was significantly below 1.00, $t(7) = 4.42$, $p < .002$, indicating that when the test mobile displayed an additional feature, it was not an effective retrieval cue for the training memory.

These findings reveal that 3-month-olds' delayed object recognition was asymmetrical. Infants detected the presence of a novel feature in the homogeneous test display but not its absence, discriminating between Rs and Ps in the feature-present condition but not in the feature-absent condition. An account of the failure to discriminate the novel feature-absent stimulus stems from evidence in the animal learning and memory literature which indicate that isolated components of an original training situation are often effective retrieval cues for the training memory (for review, see Spear, 1973; Spear & Parsons, 1976). In studies with infants, both the original training context (without the training cue) and the original training cue (without the training context) are effective retrieval cues; however, if an element that was not part of the original training situation is added to either of these, memory

TABLE 2
Mean baseline (BR) and retention (RR) ratios, *SE*s, *t*s, and *p* values for three novel test groups and a no-charge control group ($n = 8$) as a function of feature presence or absence in the test mobile in Experiments 2A and 2B

Group	*Feature Presence/ Absence*	*BR*	*SE*	*t*[a]	*p*	*RR*	*SE*	*t*[b]	*p*
				Experiment 2A (24-Hour Test)					
P/R	Present	1.40	0.22	1.83	n.s.	0.54	0.10	4.42	0.002
R/P	Absent	2.26	0.50	2.52	0.02	0.77	0.11	2.12	0.04
No Change	—	2.38	0.34	4.00	0.003	0.92	0.07	1.17	n.s.
				Experiment 2B (1-Hour Test)					
R/P	Absent	1.72	0.35	2.09	0.04	0.60	0.10	3.93	0.003

[a] Comparison with a theoretical baseline ratio of 1.00 (i.e., no retention).
[b] Comparison with a theoretical retention ratio of 1.00 (i.e., no retention deficit).

retrieval is completely precluded (Butler & Rovee-Collier, 1989; Hayne & Findlay, 1995; Hayne, Greco, Earley, Griesler, & Rovee-Collier, 1986; Rovee-Collier, Schechter, Shyi, & Shields, 1992). Thus, both animal and infant studies indicate that any cue which is a subset of the information originally encoded during training is effective in retrieving the memory representation. By this account, any stimulus that shares all of its features with the training stimulus (i.e., P is a component or subset of R) will strike a match with the contents of long-term memory and retrieve the training memory.

That infants noticed the presence of a novel perceptual primitive but not its absence in the 24-hr memory task was predicted by asymmetries in adult visual search (Treisman, 1988; Treisman & Gormican, 1988; Treisman & Souther, 1985), texture segregation (Beck, 1973; Julesz, 1981) and infant visual preference (Colombo et al., 1995). The present experiment, however, does not allow us to conclude why infants failed to discriminate Ps from Rs during the 24-hr test. Furthermore, the current failure to discriminate the novel feature-absent cues indicate that infants' exhibition of partial retention in Experiment 1 could not simply be due to impairment by novel feature-absent cues in the pop-out display. Studies have indicated that working memory is the workplace in which retrieval, recognition, and discrimination occur (for a review, see Baddeley, 1994). Taken together, these findings suggest that, in the pop-out display, the familiar feature-present cues are required to retrieve those same details from the long-term memory of training into working memory in order to differentiate the deletion of a feature. Perhaps, similarly, in the present experiment, infants could initially discriminate the absence of the feature that distinguishes P from R when the training details were accessible to working memory but forgot them over the retention interval. In a follow-up experiment, therefore, we examined this possibility by testing infants after a shorter delay, when the original details would still be accessible to working memory.

EXPERIMENT 2B: 1-HR TEST WITH A NOVEL HOMOGENEOUS DISPLAY

In Experiment 2A, infants discriminated the addition of a novel feature to the test display but not its deletion 24 hrs after training. This could have occurred because they forgot the distinguishing feature after the 24-hr delay, such that it was not accessible for comparison in working memory. In a previous study, infants of the same age failed to discriminate Ls from Ts after 24 hrs (Rovee-Collier et al., 1992) but not after only 1 hr (Adler & Rovee-Collier, 1994). The latter finding indicated that infants' lack of discrimination after 24 hrs was due not to their inability to perceptually distinguish Ls from Ts per se but to their forgetting the details that distinguish Ls from Ts (the spatial arrangement of the line segments and/or the number of line terminators).

In Experiment 2B, therefore, we asked whether infants who were trained with Rs could discriminate Ps from Rs during a 1-hr delayed recognition test. If their failure to discriminate was due to forgetting of the detail that distinguished Rs from Ps, then they might discriminate between these stimuli after the shorter delay when the detail would still be accessible to working memory.

Method

Participants

Eight healthy, full-term 3-month-old infants (5 males, 3 females) were recruited as before. Their ages ranged from 92 to 112 days on the first day of training (M = 102.9 days, SD = 7.3). Additional infants who cried longer than 2 consecutive minutes in any of the three sessions (n = 1) or failed to reach the learning criterion (n = 1) were excluded from the final sample.

Apparatus and Procedure

The apparatus and the training and testing procedures were identical to those of *group R/*

P in Experiment 2A. In Experiment 2B, however, infants were trained for 2 consecutive days with an R mobile and were tested with a P mobile only 1 hr later.

RESULTS AND DISCUSSION

Directional *t* tests indicated that infants failed to detect the absence of the familiar feature that distinguished R from P even though their memory load was reduced by testing after a shorter delay. Similar to the partial retention of *group R/P* in Experiment 2A, the present group's mean baseline ratio was significantly above a theoretical baseline ratio of 1.00, $t(7) = 2.09$, $p < .04$, and its mean retention ratio was significantly less than a theoretical retention ratio of 1.00, $t(7) = 3.93$, $p < .003$ (see Table 2).

We conclude, therefore, that infants in the present experiment, as in Experiment 2A, failed to discriminate the P from the training R because they were unable to perceptually distinguish the absence of the detail in the R at the time of retrieval. The efficacy of the P to be a retrieval cue for R may reflect one of two possible mechanisms. First, the single specific feature that distinguished R from P may have been forgotten rather rapidly and, therefore, was no longer accessible to working memory. Alternatively, the additional feature in the R may not have been forgotten and, instead, retrieval was the functional consequence of the isolated featural components of the P matching the memory representation of the R. Recall, however, that Adler and Rovee-Collier (1994) found that infants of the same age discriminated Ls from Ts after 1 hr when they had failed to do so after 24 hrs (Rovee-Collier et al., 1992). This indicated that the details that distinguish Ls from Ts which were forgotten after 24 hrs were accessible after 1 hr yielding discrimination, despite the fact that the isolated featural components of Ls matched those in the memory representation of Ts. In the present experiment, if the distinguishing detail of the R was still accessible in memory, then infants should have similarly discriminated the novel P test mobile even though all of its isolated featural components had complementary components in the memory representation of the R. The fact that infants did not discriminate suggests that the differentiating detail in the R was not accessible in memory and had been forgotten by the 1 hr test.

In either case, the information in the P test mobile, as a subset of an R, exactly matched the information that remained accessible from the original memory representation of the R, resulting in recognition. Exhibition of partial retention in both Experiments 2A and 2B suggests that after successful retrieval of the originally encoded details of the R into working memory, comparison of the novel P to the retrieved details impaired infants' significant retention. This further supports the contention that in Experiment 1 the impairment by the novel P of the exhibited retention was due to the familiar R retrieving the differentiating detail (i.e., the horizontal line) into working memory. Thus, perceptual asymmetry determines which stimulus in the visual array is initially attended and, if an effective retrieval cue, the information that is consequently retrieved into working memory to which subsequently attended sensory information is compared.

GENERAL DISCUSSION

At the outset of these experiments we had asked whether asymmetries in feature detection, which have been reported for both adults (e.g., Treisman & Souther, 1985) and infants (Colombo et al., 1995), might affect infants' detection of effective retrieval cues in a long-term memory paradigm in which some predictive significance had previously been associated with the feature-present or feature-absent test targets. In complete agreement with these previous studies, we found a robust perceptual asymmetry in visual pop-out—a feature-present target popped out but a feature-absent target did not. As a consequence, the familiarity or novelty of the feature-present stimulus, whether as target or distractor, determined whether retention or a retrieval failure was exhibited. When the feature-present stimulus was familiar, however, the exhibited retention was partially impaired, suggesting that the feature-absent stimulus was at least partly attended when it was novel. This difference in present and past findings for feature-absent test stimuli reflects the fact that we inferred attention from infants' performance of a previously learned behavior whereas Colombo et al. (1995) had inferred attention from infants' looking behavior (e.g., visual preference). That the novel feature-absent stimulus was detected on some level and did yield evidence of impaired recognition undoubtedly reflects our use of a 3-min test that involved the retrieval of information from memory; Colombo et al., for example, had used only a 5-s test without any previous familiarization with the stimuli and had required only perceptual detection.

An alternative explanation for the data of Experiment 1 is that visual pop-out did not occur and, instead, infants serially scanned the entire test mobile. Consequently, infants' recognition performance was not determined by an asymmetry in pop-out but was a factor of whether or not novel feature information is detected in the test mobile that does not match the feature information in the original training memory. When infants are trained with Rs, test mobiles consisting of both familiar Rs and novel Ps (which are perceptual subsets of Rs) contain no novel feature information and, therefore, are effective retrieval cues, yielding generalized responding. In contrast, when infants are trained with Ps, test mobiles consisting of both novel Rs and familiar Ps do contain novel feature information in the form of the distinguishing feature of the R (i.e., the diagonal line) and, therefore, are not effective retrieval cues, yielding discrimination. Thus, the determining factor for infants' recognition performance is not whether a unique item pops out from amidst its surrounding distractor but whether novel feature information is detected anywhere in the test stimulus.

Two sets of findings argue against stimulus generalization and in favor of visual pop-out. First, 3-month-olds who are trained with a multi-object mobile will discriminate a test mobile in which *more than one* of the constituent objects is different but they will not discriminate a test mobile with *only one* different object (Hayne et al., 1986). Thus, had infants' recognition performance in Experiment 1 been determined by whether or not infants detected novel information on the test mobile then the pop-out test mobiles used did not reach the critical mass of novelty, as established by the earlier study, necessary to elicit discrimination. That is, infants in *group P/P(R)*, whose test mobile contained *only one* different item, should have generalized responding; that they did not suggests that the unique novel R, via pop out, controlled infants' performance.

Second, in the original pop-out study conducted by our lab (Rovee-Collier, Hankins, & Bhatt, 1992; also see Adler, Gerhardstein, & Rovee-Collier, 1998) a pop-out control condition was included. In that condition, infants were trained with a homogeneous mobile of +s and then tested with a mobile displaying three familiar + items amidst four novel L items. While in the experimental pop-out condition, infants similarly trained recognized a pop-out mobile that displayed a single + item amidst six novel L items, in the control condition infants discriminated the 3+/4L mobile despite the fact that it was 300% more familiar than the pop-out mobile. Because all features (two line segments and line terminators) that collectively fashion an L are also present in the +, one could similarly claim that infants recognition of the pop-out mobile was due to stimulus generalization and the failure to detect any novel feature information. If so, then the 3+/4L mobile should have also been recognized because it too fails to contain any novel feature information. That infants discriminated the 3+/4L mobile indicates that stimulus generalization could not account for infants' recognition of the pop-out mobile in the original study or the present one. Instead, the best account for infants' recognition performance in Experiment 1 is one that invokes an asymmetry in the pop-out of a unique target item amidst dissimilar distractor items.

The perceptual asymmetry account of the findings of Experiment 1 requires the joint assumptions that (a) a feature-present stimulus pops out and captures initial attention while a feature-absent target does not, and (b) a novel feature-absent stimulus is secondarily attended such that the efficacy of retrieval by the familiar feature-present stimulus is impaired. According to these assumptions, there are two stimulus characteristics that can command attention, feature presence and novelty, and they are hierarchically detected. That is, primary attention is controlled by the early perceptual processing of feature presence versus feature absence and secondary attention is allocated to the presence of novelty.

The initial and immediate control of attention by the presence of a particular feature is predicted by Treisman's feature-integration theory of object recognition (Treisman & Gelade, 1980), which proposes that two different subsystems control visual information processing. In the early stage, the preattentive system decomposes a visual pattern via a parallel search process in which critical features of objects "pop-out" or call attention to themselves (Treisman, 1988). When a particular feature is present, then it activates a node on its map, enabling its immediate and automatic perception. As a consequence of the preattentive process, pop-out only determines "where" a unique item is but not "what" it is (Treisman & Gormican, 1988; Wolfe, Chun, & Friedman-Hill, 1995). The later-acting, focused-attention subsystem uses the information provided by the preattentive system to form an object file in working memory (Treisman, 1992) which enables object identification or recognition via the retrieval of information from long-term memory into working memory (Treisman & Souther, 1985). Thus, an object defined by the presence of a critical feature is immediately attended and, consequently, is the first to be matched to long-term memory for purposes of retrieval. If there is a match between the featural information provided by the preattentive system and the information stored in long-term memory then the object is recognized, if there is no match then it is not. This supports the interpretation of the results of Experiment 1 that the feature-present stimulus controlled initial attentional allocation and determined, via the matching process with long-term memory, the exhibition of recognition when familiar and of a retention failure when novel.

Novelty, however, is not one of the stimulus features that Treisman (1988) has hypothesized to be detected by the preattentive system. Yet, Wang, Cavanagh, and Green (1994) have recently found in a visual search study with adults that when the featural components of target and distractors are identical, a novel target (a backwards Z) pops out from amidst familiar distractors (regular Zs) but a familiar target does not. Moreover, one of the more robust findings in the infant literature is that they have a natural tendency to attend to novel items (Cohen, 1972; Cohen & Gelber, 1975; Colombo et al., 1995; Fagan, 1970, 1977; Fantz, 1964; Richards & Casey, 1992). These findings indicate that the stimulus characteristic of novelty is capable of commanding attention.

The results of Experiment 1 suggest that novelty is a secondary stimulus characteristic that is attended only after immediate attention is controlled by the stimulus feature of feature-presence that is processed by the preattentive system. As a consequence of commanding subsequent attention, novelty would not have a direct effect on memory retrieval but would only modulate performance after retrieval of information into working memory has been initiated by the immediately attended cue. Baddeley and Hitch (1974) refer to working memory as the place for retrieval and comparison between information from long-term memory and the perceptual environment. Baddeley (1994) has further indicated that due to the limited capacity of working memory, perceptual information from different sources is not available simultaneously; for example, visual information may arrive before auditory information (also see Weldon, 1993). Moreover, the limited capacity of working memory has been shown to be in a linear relationship with age (de Ribaupirre & Bailleux, 1994; Henry, 1994; Walker, Hitch, Doyle, & Porter, 1994). It is not difficult, therefore, to hypothesize that due to the hierarchical nature of attending to different stimulus characteristics, information from within a single modality is not simultaneously available to working memory. Objects that are defined by stimulus features, such as those detected by the preattentive system, that are immediately attended would arrive in working memory first and initiate the retrieval process while those objects that are defined by characteristics which are subsequently attended (novelty) can only modulate that retrieval.

Such a relation between the secondary control of attention by novelty and working memory is indicated by the findings of Experiment 1 in which the familiar feature-present cue (R) controlled exhibition of recognition after a delay of 24 hrs by initiating retrieval of training details into working memory, but whose efficacy was impaired by subsequent comparison of the novel feature-absent cue (P) with the information already retrieved into working memory. This effect is further supported by both Experiments 2A and 2B in which making the detail that distinguishes Ps from Rs available to working memory by initiating retrieval with a cue that is a perceptual subset (P) of the originally encoded cue (R), recognition is subsequently impaired by the novelty of that retrieval cue. When working memory is provided with the perceptual feature that differentiates Ps from Rs by retrieval mediated by the immediately attended familiar feature-present cue (Experiment 1) or mediated by a perceptually indistinguishable cue (Experiments 2A and 2B), impaired recognition is exhibited. Thus, while the perceptual asymmetry determines which cue is immediately attended and whether retrieval is initiated, stimulus cues or characteristics of the same cue that have secondary control of attention contribute to the recognition process.

To conclude, the present study indicates that the factors that determine whether or not an effective retrieval cue is detected also will determine whether or not the training representation is retrieved from long-term memory. A decade ago, Treisman (1986) suggested that pop-out provides the stimulus information necessary for the recognition and identification of a target object by virtue of its comparison with the contents of long-term memory. The present study, however, is the first to directly investigate the proposed functional relation between perceptual asymmetry and retrieval from long-term memory with participants of any age. Although perceptual asymmetry appears to be ubiquitous across ontogeny, we conclude that its functional significance for retrieval from long-term memory is not. While perceptual asymmetry is primary in determining which cue initiates retrieval, subsequently attended cues based on secondary stimulus characteristics can modulate recognition performance. Moreover, the effect on recognition performance by subsequently attended cues or characteristics of the same cue depends on the retrieval of the original details into working memory by the immediately attended (perceptual asymmetry based) cue.

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NOTES

1. The asymmetry found by Allan and Blough (1989) for pigeons was the reverse of that reported by Williams and Julesz (1992) and may be a species-specific difference associated with the shape of grain.
2. Treisman, Vieira, and Hayes (1992) have indicated that preattentive processing and the pop-out effect does not require extended practice. Ahissar and Hochstein (1995), however, have found that the reaction time associated with the pop-out can be decreased with practice. One might argue, therefore, that prior conditioning of the infants may affect whether or not pop-out was exhibited. Two points negate this argument: First, there was no difference among the groups in their final level of conditioning and, second, infants were not trained with a pop-out display as was the case in the Ahissar and Hochstein study.

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