The Effect of Object Color on Episodic Memory

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Abstract

This study employed ERP technology and a study-recognition paradigm to investigate how consistency between visually presented colors and object color knowledge in memory influences episodic memory encoding and retrieval. The results demonstrated that during encoding of object pictures, color-incongruent pictures elicited a larger N400, whereas during retrieval, color-congruent pictures received more familiarity processing (Experiment 1). Object names activated typical color knowledge more rapidly, and color-congruent names elicited more detailed recollection (LPC positivity) (Experiment 2). The findings indicate that color congruence facilitates memory encoding at the perceptual level while impeding semantic-level encoding. Simultaneously, color congruence promotes both familiarity and recollection processes in object picture retrieval (perceptual level), whereas for object name retrieval (conceptual level), the facilitative effect is manifested solely in recollection. Moreover, color is intimately linked with object names and similarly influences the semantic representation of objects, supporting the activation-spreading model theory. This study provides evidence at both perceptual and conceptual levels for elucidating the role of object color in associative memory.

Full Text

The Influence of Object Color on Episodic Memory

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Abstract

This study employed ERP technology and a study-test paradigm to investigate how consistency between visually presented color and stored object color knowledge affects the encoding and retrieval of episodic memory. The results revealed that during encoding, color-inconsistent pictures elicited larger N400 responses, while during retrieval, color-consistent pictures received more familiarity processing (Experiment 1). Object names activated typical color knowledge more rapidly, with color-consistent names showing greater recollection of details (reflected by enhanced LPC) (Experiment 2). These findings indicate that color consistency facilitates memory encoding at the perceptual level but impedes it at the semantic level. Moreover, color consistency promotes both familiarity and recollection processes in object picture retrieval (perceptual level), whereas for object name retrieval (conceptual level), the facilitative effect manifests only in recollection. Additionally, color is intimately linked with object names and similarly influences semantic representations of objects, supporting the spreading activation model. This study provides electrophysiological evidence for the role of object color in associative memory from both perceptual and conceptual perspectives.

Keywords: color diagnosticity; episodic memory; ERPs; familiarity; recollection
Classification Code: B842

Episodic memory refers to an individual's memory of specific events and experiences occurring in particular temporal and spatial contexts. Item memory pertains to memory for individual items within an episode, whereas associative memory involves memory for relationships between items or between items and context (Cohen & Eichenbaum, 1993; Konkel & Cohen, 2009; Liang & Guo, 2012). In intra-item associative memory, items become bound with their perceptual features, such as words with font color, objects with location, or object color with shape (Mayes, Montaldi, & Migo, 2007). Thus, the encoding, representation, storage, and retrieval of different object features constitute essential aspects of intra-item associative memory.

As a fundamental object attribute, color facilitates object recognition (Lewis, Pearson, & Khuu, 2013; Vernon & Lloyd-Jones, 2003). The "Shape+Surface" model of object recognition (Tanaka, Weiskopf, & Williams, 2001) (see [Figure 1: see original paper]) distinguishes between surface color and color knowledge. Surface color refers to the actual color of an object during perception (e.g., a red strawberry), whereas color knowledge represents the object's typical color information (e.g., strawberries are usually red) acquired through long-term experience and stored in semantic or visual form in long-term memory. Object color knowledge can be activated by both visual images (perception) and verbal labels (concepts), though verbal labels activate object color knowledge more readily than direct visual representations (Huettig & Altmann, 2011; Naor, Tarr, & Kersten, 2003).

[Figure 1: see original paper] The "Shape+Surface" recognition model (adapted from Tanaka, Weiskopf, & Williams, 2001)

The retrieval of object color knowledge relates to color diagnosticity—the degree to which a color is associated with or symbolizes a particular object (Tanaka

& Presnell, 1999). For instance, yellow is strongly associated with bananas, whereas combs have no specific associated color. Meta-analytic research (Bramão, Reis, Petersson, & Faísca, 2011) demonstrates that color significantly facilitates recognition of high color diagnosticity objects because their mental representations are activated both bottom-up by color perception and top-down by color knowledge (Bramão, Faísca, Petersson, & Reis, 2010; Bramão, Reis, Petersson, & Faísca, 2016). Thus, binding color with other features enhances color diagnosticity in objects, thereby facilitating both low-level perceptual processing and high-level cognitive retrieval during encoding and representation (Spence, Wong, Rusan, & Rastegar, 2006; Teichmann et al., 2020).

In visual long-term memory, information representation comprises two independent subsystems: a feature-based system that stores visual experiences as independent features, and an object-based system that stores visual information as whole objects. These systems can flexibly store input information according to task demands (Spachtholz & Kuhbandner, 2017; Song, Liu, Lu, & Gu, 2016). Consequently, how objects and their features (such as color) are encoded and represented in memory systems influences information storage and retrieval. This occurs because color improves the connection function of neural networks and enhances brain information processing efficiency (Chai et al., 2019); it increases attentional arousal, prioritizing the processing of colored objects (Lee, Leonard, Luck, & Geng, 2018); and it strengthens memory encoding, increasing the likelihood that stimuli will be successfully encoded, stored, and retrieved, thereby improving memory performance (Dzulkifli & Mustafar, 2013).

In episodic memory, color and color knowledge not only affect the mental representation and encoding of objects; during retrieval, both newly formed temporary shape-color associations and more stable shape-color associations stored in long-term memory interact to either hinder or facilitate intra-item associative memory retrieval (Yonelinas, 2002). Therefore, object information in episodic memory involves not only independent features such as color and shape but also relationships between features (binding). According to the "Surface+Shape" model (Tanaka et al., 2001), both object images and verbal labels can activate stored color knowledge (visual color knowledge, semantic color knowledge), representing low-level perceptual processing and high-level semantic (conceptual) processing, respectively. In other words, color possesses both abstract (semantic) and concrete (visual) dual characteristics. For example, "seeing a red apple" and "knowing that apples are red" represent different cognitive operations on color. The former involves color perception, while the latter involves retrieval of object color knowledge; these two processes interact.

According to dual-process theory of memory, recognition retrieval in episodic memory comprises two fundamental components: familiarity and recollection (Brainerd, Reyna, & Kneer, 1995; Hintzman & Curran, 1994; Jacoby, 1991; Mandler, 1980; Yonelinas, 1994). Familiarity refers to the extraction of information strength (quantity) (Evans & Wilding, 2012; Yonelinas, 2002) and is regulated by both perceptual and conceptual variables (Boldini, Algarabel, Ibañez,

& Bajo, 2008), involving both perceptual and conceptual processing (Bruett & Leynes, 2015; Yonelinas, 2002). It is sensitive to intrinsic object features but unaffected by contextual information (Ecker, Zimmer, & Groh-Bordin, 2007). Familiarity is primarily manifested as the ERP old/new effect in the frontal region (FN400, Frontal Negativity) between 300-500 ms (Curran, 2000; Rugg & Curran, 2007). Recollection, in contrast, involves extraction of information quality (Evans & Wilding, 2012; Yonelinas, 2002), pointing more toward conceptual processing (Bruett & Leynes, 2015; Yonelinas, 2002), and is modulated by both inherent (typical color, shape, etc.) and temporary (atypical color, context) information (Ecker et al., 2007). It depends on the interaction between encoding processes, current information features, and memory context (Leynes & Crawford, 2018). Recollection is primarily manifested as the scalp ERP old/new effect in the left parietal region between 400-800 ms (Curran, 2000; Rugg & Curran, 2007).

In summary, color input can activate both perceptual (visual) and conceptual (semantic) representations in memory systems; these two representations interact to facilitate object information recognition retrieval (Lu et al., 2010). The recognition retrieval process necessarily involves both familiarity and recollection components. However, to date, a comprehensive understanding of the relationship between different processing levels (perceptual vs. conceptual) of object color information and episodic memory retrieval components (familiarity vs. recollection) remains lacking. On one hand, although most behavioral and ERP studies indicate that objects correctly bound with color (yellow bananas) show better recognition than incorrectly bound objects (purple bananas), and that color changes interfere with episodic memory retrieval (Dzulkifli & Mustafar, 2013; Mayes et al., 2007; Vernon & Lloyd-Jones, 2003), other research (Ludajić & Zdravković, 2016; Tanaka et al., 2001) suggests that object shape is more important for recognition, with color facilitating recognition only when shape is ambiguous or absent. Furthermore, Cycowicz, Nessler, Horton, and Friedman (2008) used sketches of objects in natural and unnatural colors as stimuli in a study-test paradigm and found that, in an item recognition memory task, unnatural color objects elicited more positive ERP responses between 500-600 ms compared to natural color objects. Cycowicz et al. argued that unnatural color objects are more novel, generating more semantic activation and contextual cues during encoding, along with greater recollection, thereby facilitating their recognition retrieval.

Thus, the role of object color remains controversial. On the other hand, Nyhus and Curran (2009) demonstrated through semantic and perceptual feature matching tasks with words that semantic encoding tasks (conceptual) and perceptual matching of specific information in words (perceptual) yield better recognition memory by affecting familiarity (FN400, 300-500 ms) and recollection (500-800 ms, LPC, late positive component) processes. However, Nyhus et al.'s study did not involve color. Cui, Gao, Zhou, and Guo (2016) used unnatural objects (artificial shapes) under perceptual processing (judging object color or shape) and conceptual processing (imagining stimuli as meaningful objects) conditions to explore how object color changes affect episodic recognition retrieval. Their results showed that in both tasks, recognition accuracy was higher for color-consistent than inconsistent items, with color changes significantly affecting recognition accuracy. Although both tasks showed clear familiarity (recognition memory performance far above chance level), FN400 effects appeared only in the conceptual processing task, not the perceptual processing task. Cui et al. used unnatural objects with temporary color-object associations that could not reflect the role of high color diagnosticity (object color knowledge). Additionally, their conceptual level processing task used an "imagination" task, which is subject to large individual differences. For high color diagnosticity objects, color information activates associations between shape and typical color, participating top-down in object mental representation and processing (Dzulkifli & Mustafar, 2013). Therefore, investigating the role of object color in the relationship between different processing modes (perceptual and semantic) and recognition retrieval components (familiarity and recollection) from the perspective of natural objects (considering color diagnosticity) can help better understand the nature of episodic memory retrieval.

Features such as object shape and color in memory systems are encoded synergistically, stored independently, and retrieved interactively (Kuhbandner, Spitzer, Lichtenfeld, & Pekrun, 2015; Vurro, Ling, & Hurlbert, 2013). Visual color at the perceptual level and long-term memory encoding activated by perceptual processing both have perceptual properties. Therefore, during perceptual judgment, visual color has a facilitative effect, while during recognition retrieval it tends to cause interference. Conversely, in conceptual level processing, the difference between visual color and semantic color knowledge of objects in memory is substantial, hindering and delaying semantic judgment but causing less interference during recognition retrieval. Since perceptual and semantic representations interact when retrieving object information (Lu et al., 2010), and familiarity is regulated by both perceptual and conceptual variables (Boldini et al., 2008), visual color has a relatively large impact at both perceptual and conceptual levels. Recollection processes activate more representations of item details (name color) (Yonelinas, 2002), while activation of object semantic color knowledge (natural color) is relatively greater, making it more susceptible to visual color influence. We therefore hypothesize that color information facilitates memory encoding at the perceptual processing level but shows an inhibitory effect at the conceptual level. During recognition retrieval, color information affects both familiarity and recollection at the perceptual level, whereas at the conceptual level, recollection is more affected than familiarity. To test these hypotheses, this study used ERP technology and a study-test paradigm with two experiments employing pictures and names of high color diagnosticity objects as materials. Experiment 1 involved perceptual level processing (object picture judgment), while Experiment 2 involved conceptual level processing (object name judgment), to explore how consistency between visual color input and object color knowledge affects associative memory encoding and retrieval in episodic memory. We predicted that during encoding, perceptual level conditions would show better perceptual judgment performance for color-consistent than inconsistent items, while conceptual level conditions would show the opposite pattern. ERP differences between color-consistent and inconsistent items would be observed in perceptual level conditions but not in conceptual level processing. During retrieval, perceptual processing conditions would show more pronounced FN400 and LPC old/new effects, with color-consistent items eliciting larger ERP responses than inconsistent items; conceptual processing conditions would show only larger LPC old/new effects.

Experiment 1: The Influence of Color on Episodic Memory for Object Pictures

2.1.1 Participants

Twenty-eight university students (13 male, 15 female) aged 22-25 years (mean age = 23.59 years) participated in the experiment. Based on previous research (Cycowicz et al., 2008), the target effect size ω^2 was calculated as 0.64. According to G*Power 3.1 software, a repeated-measures F-test with statistical power 1-β = 0.80 and α = 0.05 required a sample size of 21 participants. All participants were right-handed with normal or corrected-to-normal vision, normal color vision, and no history of psychiatric or neurological disorders. Participants received monetary compensation after the experiment.

2.1.2 Materials and Apparatus

We selected pictures of highly familiar everyday objects with typical colors, such as celery, bananas, frogs, and pine trees. Pictures subtended approximately 2° × 2° of visual angle and were presented on a white background. Forty university students rated object familiarity on a 5-point scale (1 = very unfamiliar, 5 = very familiar), and pictures with ratings above 4.0 were selected. Using drawing software, each object picture was rendered in two different colors: color-consistent pictures matching the object's actual typical color and color-inconsistent pictures mismatching the object's typical color. Another 40 university students rated the consistency between picture color and real-world object color on a 5-point scale (1 = very inconsistent, 5 = very consistent). Pictures with consistency ratings above 4.0 were defined as color-consistent, and those below 2.0 as color-inconsistent. Only one version (color-consistent or color-inconsistent) of each object entered the experimental material pool, with 128 pictures per condition, totaling 256 object pictures.

EEG was recorded continuously using a Neuroscan 64-channel recording system with Ag/AgCl electrodes according to the extended 10/20 system. Four additional electrodes recorded eye movements: two above and below the left orbit for vertical electrooculogram (VEOG) and two at the outer canthi of both eyes for horizontal electrooculogram (HEOG). Reference electrodes were placed on the left and right mastoids, and the ground electrode was located at the midpoint between FPz and Fz. The A/D sampling rate was 500 Hz, and electrode impedance was maintained below 5 kΩ. Stimuli were presented on a 19-inch monitor approximately 80 cm from participants, and the experimental procedure was controlled by E-Prime software.

2.1.3 Experimental Design

The experiment employed a 2 (color consistency: consistent vs. inconsistent) × 2 (picture novelty: new vs. old) within-subjects design using a study-test paradigm. The independent variable during the study phase (encoding) was color consistency (consistent vs. inconsistent). During the test phase (retrieval), the independent variables were color consistency (consistent vs. inconsistent) and picture novelty (new vs. old).

2.1.4 Procedure

[**Figure 2: see original paper**] Experimental procedure for Experiment 1

The experimental flow is illustrated in [Figure 2: see original paper]. During the study phase, a fixation cross "+" appeared at the center of the screen for 400-600 ms, followed by an object picture for 500 ms. After picture offset, a blank screen appeared for 1000 ms. Participants judged whether the presented picture's color matched the object's natural color and responded as quickly as possible with left/right hand key presses. This process repeated for each picture. After studying 16 pictures (half color-consistent, half color-inconsistent), a three-digit number appeared at the center of the screen, and participants performed serial subtractions of three, reporting answers aloud for one minute to prevent rehearsal of the previously presented stimuli. Subsequently, a recognition test was administered for 32 pictures (16 old, 16 new). The recognition phase procedure was similar to the study phase, except participants judged whether each picture had been studied previously. There were 128 old and 128 new pictures (64 consistent and 64 inconsistent each), divided into eight study-test blocks, with different picture types presented randomly. Participants were instructed to respond as quickly and accurately as possible, minimize blinking during stimulus presentation, and respond with counterbalanced left/right key assignments across participants. Practice trials were administered before the formal experiment.

2.1.5 EEG Data Analysis

During offline analysis, EEG data were re-referenced to the average of the left and right mastoids, with a -100 to 0 ms pre-stimulus baseline correction. Trials with blinks, muscle artifacts, or incorrect responses were excluded using a $\pm$75 V criterion, and a 0.01-40 Hz bandpass filter was applied. During the study phase, object representation occurs during 300-500 ms post-stimulus (Schendan & Kutas, 2002), which corresponds to the N400 time window for semantic acquisition in word comprehension (Balass, Nelson, & Perfetti, 2010). Following Lu et al. (2010), we selected 375-475 ms as the N400 observation window (early object identification stage) and 500-700 ms (P600) as an index of late object identification (Schendan & Kutas, 2002, 2003). During the retrieval phase, we selected 300-500 ms and 500-800 ms as time windows corresponding to familiarity and recollection, respectively, based on Curran (2000) and Rugg and Curran (2007). Twelve representative electrodes were selected: frontal (F3, Fz, F4), frontocentral (FC3, FCz, FC4), centroparietal (CP3, CPz, CP4), and parietal (P3, Pz, P4). Mean amplitudes for each time window and condition were calculated and analyzed statistically with factors of color consistency (consistent vs. inconsistent), picture novelty (new vs. old), and brain region (frontal, frontocentral, centroparietal, parietal). Greenhouse-Geisser correction was applied when the sphericity assumption was violated.

2.2.1 Behavioral Data

During the study phase (see [Figure 3: see original paper]), accuracy for color-consistent pictures (94.76%) was significantly higher than for color-inconsistent pictures (88.11%) [$F(1,26) = 30.73$, $p < 0.001$, $^2 = 0.54$], and response times were significantly faster for color-consistent pictures (676.39 ms) than for color-inconsistent pictures (717.72 ms) [$F(1,26) = 41.28$, $p < 0.001$, $^2 = 0.62$].

[Figure 3: see original paper] Learning and recognition performance for object pictures under different conditions (Note: ** indicates $p < 0.01$)

Recognition phase results are shown in [Figure 3: see original paper]. A 2 (color consistency) × 2 (picture novelty) repeated-measures ANOVA on recognition accuracy revealed that accuracy for color-consistent pictures (91.10%) was significantly higher than for color-inconsistent pictures (84.60%) [$F(1,26) = 36.40$, $p < 0.001$, $^2 = 0.58$], and accuracy for new pictures (90.30%) was significantly higher than for old pictures (85.40%) [$F(1,26) = 6.70$, $p = 0.016$, $^2 = 0.21$]. The interaction between color consistency and picture novelty was significant [$F(1,26) = 47.30$, $p < 0.001$, $^2 = 0.65$]. Simple effects analysis indicated that for old pictures, recognition accuracy for color-consistent pictures (94.35%) was significantly higher than for color-inconsistent pictures (76.46%) [$F(1,26) = 59.45$, $p < 0.001$, $^2 = 0.70$], whereas for new pictures, no significant difference existed between color-consistent (87.86%) and color-inconsistent (92.80%) conditions.

The interaction between color consistency and picture novelty was also significant for recognition response times [$F(1,26) = 85.47$, $p < 0.001$, $^2 = 0.77$]. Simple effects analysis revealed that for old pictures, response times for color-consistent pictures (649.95 ms) were significantly shorter than for color-inconsistent pictures (743.29 ms) [$F(1,26) = 139.62$, $p < 0.001$, $^2 = 0.84$], while for new pictures, no significant difference existed between color-consistent (718.26 ms) and color-inconsistent (720.41 ms) conditions.

2.2.2 ERP Analysis: Study Phase

We conducted separate 2 (color consistency: consistent vs. inconsistent) × 4 (brain region: frontal, frontocentral, centroparietal, parietal) repeated-measures

ANOVAs for the 375-475 ms and 500-700 ms time windows. Waveforms and difference topographies are shown in [Figure 4: see original paper].

In the 375-475 ms window, color-inconsistent pictures elicited more negative amplitudes than consistent pictures [F(1,26) = 4.77, p = 0.039, ^{2} = 0.16]. A significant main effect of brain region emerged [F(3,78) = 48.21, p < 0.001, ^{2} = 0.66], with more negative amplitudes at frontal and frontocentral regions than at centroparietal and parietal regions (ps < 0.001). The interaction between color consistency and brain region was significant [F(3,78) = 3.32, p = 0.024, ^{2} = 0.12]; at frontal sites, color-inconsistent pictures elicited significantly more negative amplitudes [F(1,26) = 7.61, p = 0.011, ^{2} = 0.23].

In the 500-700 ms window, no significant main effect of color consistency emerged. The main effect of brain region was significant [F(3,78) = 39.80, p < 0.001, ^{2} = 0.62], with more negative amplitudes at frontal and frontocentral regions than at centroparietal and parietal regions (ps < 0.001). The interaction between color consistency and brain region was not significant. Thus, during 375-475 ms, color-inconsistent pictures elicited larger negative waveforms (N400) at frontal and frontocentral regions, indicating clear semantic conflict.

[Figure 4: see original paper] ERP waveforms for color-consistent and color-inconsistent pictures during the study phase and difference wave (color-consistent minus color-inconsistent) topographies

2.2.3 ERP Analysis: Retrieval Phase

For the retrieval phase, we conducted 2 (color consistency: consistent vs. inconsistent) × 2 (novelty: new vs. old) × 4 (brain region: frontal, frontocentral, centroparietal, parietal) repeated-measures ANOVAs for the 300-500 ms and 500-800 ms time windows. Waveforms and difference topographies are shown in [Figure 5: see original paper].

(1) FN400 Old/New Effect Analysis (300-500 ms)

In the 300-500 ms window, the main effect of color consistency was significant [F(1,26) = 9.20, p = 0.006, ^{2} = 0.27], with color-inconsistent pictures eliciting more negative amplitudes. The main effect of picture novelty was significant [F(1,26) = 29.18, p < 0.001, ^{2} = 0.54], with old pictures eliciting more positive amplitudes than new pictures. The main effect of brain region was significant [F(3,78) = 37.30, p < 0.001, ^{2} = 0.60], with more negative amplitudes at frontal and frontocentral regions (ps < 0.001). The interaction between picture novelty and brain region was significant [F(3,78) = 7.65, p < 0.001, ^{2} = 0.23]; simple effects analysis revealed significant old/new differences across all brain regions [F(1,26) = 16.74, p < 0.001, ^{2} = 0.40; F(1,26) = 20.01, p < 0.001, ^{2} = 0.45; F(1,26) = 38.26, p < 0.001, ^{2} = 0.61; F(1,26) = 37.32, p < 0.001, ^{2} = 0.60], with old pictures eliciting more positive amplitudes, demonstrating the early FN400 old/new effect. The interaction between color consistency and brain region was significant [F(3,78) = 4.51, p = 0.006, ^{2} = 0.15]; simple effects analysis indicated that color-inconsistent pictures elicited more negative amplitudes at frontal, frontocentral, and centroparietal regions [$F(1,26) = 15.56$, $p < 0.001$, $^2 = 0.38$; $F(1,26) = 10.19$, $p = 0.004$, $^2 = 0.29$; $F(1,26) = 7.12$, $p = 0.013$, $^2 = 0.22$]. The three-way interaction was not significant. These results indicate that during 300-500 ms, FN400 old/new effects occurred across all brain regions, with automatic familiarity processing for both color-consistent and color-inconsistent old pictures.

(2) LPC Old/New Effect Analysis (500-800 ms)

In the 500-800 ms window, the main effect of brain region was significant [$F(3,78) = 30.34$, $p < 0.001$, $^2 = 0.55$], with more negative amplitudes at frontal and frontocentral regions ($ps < 0.001$). The interaction between picture novelty and color consistency was significant [$F(1,26) = 4.71$, $p = 0.04$, $^2 = 0.16$]. Simple effects analysis revealed that for color-inconsistent pictures, the difference between old and new pictures was marginally significant [$F(1,26) = 3.54$, $p = 0.07$, $^2 = 0.12$], with old pictures eliciting more positive amplitudes, showing an LPC old/new effect. For color-consistent pictures, no significant old/new difference emerged. The interaction between picture novelty and brain region was significant [$F(3,78) = 6.95$, $p < 0.001$, $^2 = 0.22$]; simple effects analysis indicated significant old/new differences at centroparietal and parietal regions, with old pictures eliciting more positive amplitudes [$F(1,26) = 4.52$, $p = 0.04$, $^2 = 0.15$; $F(1,26) = 5.10$, $p = 0.03$, $^2 = 0.17$]. No other interactions were significant. These results indicate that during 500-800 ms, color-inconsistent conditions elicited LPC old/new effects primarily at centroparietal and parietal regions, suggesting that participants engaged in more detailed recollection.

[**Figure 5: see original paper**] Old/new effects under different color consistency conditions during the retrieval phase and old/new effect (old minus new) topographies

2.3 Discussion

In Experiment 1's study phase, participants showed higher accuracy and faster response times for color-consistent than color-inconsistent pictures, consistent with Vernon and Lloyd-Jones (2003). When encoding pictures of high color diagnosticity objects, participants activated the object's mental representation and color knowledge from long-term memory, which influenced the recognition process top-down (Bramão, Faísca et al., 2011). When object picture color matched the stored shape-color association in long-term memory, judgments were more accurate and rapid. ERP analysis revealed that during 375-475 ms (N400), color-inconsistent pictures elicited more negative waveforms than consistent pictures. Regarding N400 significance (Kutas & Hillyard, 1980), on one hand, the conflict between object color and its typical color elicited larger N400; on the other hand, this may indicate that identifying color-inconsistent object pictures requires more semantic processing. This aligns with research on color's influence on object recognition (Bramão, Reis et al., 2011; Bramão et al., 2012, 2016). Schendan and Kutas (2002, 2003) divided object recognition into early (N350 or N400) and late (P600) stages. The ERP results from Experiment 1 suggest that color semantic conceptual representation in colored object recognition occurs primarily during the early stage.

Recognition performance showed that color-consistent old pictures were recognized more accurately and rapidly than color-inconsistent old pictures. For new pictures, no significant differences existed between color-consistent and color-inconsistent conditions in accuracy or response time. Thus, during information retrieval, color knowledge in long-term memory facilitated recognition of color-consistent pictures while hindering or interfering with recognition of color-inconsistent pictures. During recognition retrieval, the FN400 effect (300-500 ms) represents familiarity for items without detailed information, a rapid automatic process (Stróżak, Bird, Corby, Frishkoff, & Curran, 2016). In Experiment 1, old pictures elicited more positive ERP amplitudes than new pictures during 300-500 ms, demonstrating early FN400 old/new effects across all brain regions, with no significant difference in old/new effect magnitude between color-consistent and inconsistent conditions. This indicates that automatic item familiarity occurred for both color-consistent and color-inconsistent old pictures. During 500-800 ms, color-inconsistent old pictures elicited larger amplitudes than new pictures, showing an LPC old/new effect concentrated at centroparietal and parietal regions. No significant old/new effect was found for color-consistent pictures. The LPC component reflects relatively slow, effortful controlled processing that indicates recollection of specific background and detail information about encoded items (Yonelinas, 2002). The results suggest that participants engaged in more detailed recollection when retrieving color-inconsistent old items, with activation of color knowledge participating in object representation and requiring more detailed recall. In contrast, recollection of color-consistent pictures required fewer details and was faster (shorter latency). Thus, color information facilitated recollection retrieval of color-consistent pictures while delaying recollection of color-inconsistent pictures.

Experiment 2: The Influence of Color on Episodic Memory for Object Names

Experiment 1 demonstrated that color knowledge affects both encoding and retrieval of episodic memory for high color diagnosticity object pictures. In long-term memory, information is primarily stored through semantic encoding, and memory differences between color-consistent and color-inconsistent objects involve activation of color semantic knowledge. According to the "Surface+Shape" model, both object images and verbal labels can activate stored color knowledge (visual color knowledge, semantic color knowledge), with verbal labels activating object color knowledge more readily than direct visual perception (Huettig & Altmann, 2011), representing low-level visual processing and high-level semantic processing, respectively. Therefore, Experiment 2 used object names as materials to investigate the influence of color on episodic memory at the conceptual level.

3.1.1 Participants

Twenty-five university students (10 male, 15 female) aged 18-25 years (mean age = 21.53 years) participated in the experiment. All were right-handed with normal or corrected-to-normal vision, no color blindness or weakness, and no history of psychiatric or neurological disorders. Participants received monetary compensation after the experiment.

3.1.2 Materials and Apparatus

High color diagnosticity object names were presented in text form, with each name written in different colors. One font color matched the object's typical color (color-consistent name, e.g., "apple" in red), while the other font color mismatched the object's typical color (color-inconsistent name, e.g., "pineapple" in blue). The font was bold Song typeface, subtending approximately 2° × 2° of visual angle.

3.1.3 Experimental Design

The experimental design was identical to Experiment 1.

3.1.4 Procedure

[**Figure 6: see original paper**] Experimental procedure for Experiment 2

The procedure, programmed with E-Prime software, is illustrated in [Figure 6: see original paper]. The experimental process was identical to Experiment 1, except that object name words replaced pictures as materials.

3.2.1 Behavioral Results

During the encoding phase (see [Figure 7: see original paper]), discrimination accuracy for color-consistent names (81.90%) was significantly lower than for color-inconsistent names (92.90%) [$F(1,24) = 57.23$, $p < 0.001$, $^2 = 0.71$]. Response times did not differ significantly (798.89 ms vs. 788.97 ms).

[**Figure 7: see original paper**] Learning and recognition performance for object names under different conditions (Note: * indicates $p < 0.05$, ** indicates $p < 0.01$)

Recognition phase results are shown in [Figure 7: see original paper]. A 2 (color-name consistency) × 2 (novelty: old vs. new) repeated-measures ANOVA on recognition accuracy revealed a significant interaction between color-name consistency and novelty [$F(1,24) = 58.42$, $p < 0.001$, $^2 = 0.71$]. Simple effects analysis indicated that for old names, accuracy for color-consistent names (92.31%) was significantly higher than for color-inconsistent names (72.39%)

[F(1,24) = 66.75, $p < 0.001$, $^2 = 0.74$]. For new names, accuracy for color-consistent names (87.82%) was significantly lower than for color-inconsistent names (92.33%) [F(1,24) = 7.12, p = 0.013, $^2 = 0.23$].

For response times, the interaction between color-name consistency and novelty was significant [F(1,24) = 53.93, $p < 0.001$, $^2 = 0.69$]. Simple effects analysis revealed that for old names, response times for color-consistent names (723.08 ms) were significantly shorter than for color-inconsistent names (797.50 ms) [F(1,24) = 62.85, $p < 0.001$, $^2 = 0.72$]. For new names, response times for color-inconsistent names (729.33 ms) were significantly faster than for color-consistent names (746.65 ms) [F(1,24) = 12.83, p = 0.002, $^2 = 0.35$].

3.2.2 ERP Analysis: Study Phase

EEG analysis during the study phase (see [Figure 8: see original paper]) involved 2 (color-name consistency: consistent vs. inconsistent) × 4 (brain region: frontal, frontocentral, centroparietal, parietal) repeated-measures ANOVAs for the 375-475 ms and 500-700 ms time windows.

In the 375-475 ms window, no main effect of color-name consistency emerged. The main effect of brain region was significant [F(3,72) = 17.38, $p < 0.001$, $^2 = 0.42$], with more negative amplitudes at frontal and frontocentral regions than at centroparietal and parietal regions ($ps < 0.05$). The interaction was not significant. In the 500-700 ms window, no main effect of color-name consistency emerged. The main effect of brain region was significant [F(3,72) = 13.60, $p < 0.001$, $^2 = 0.36$], with more negative amplitudes at frontal and frontocentral regions than at centroparietal and parietal regions ($ps < 0.01$). The interaction was not significant. Thus, color did not influence ERPs when learning object names.

[Figure 8: see original paper] ERP waveforms for color-consistent and color-inconsistent names during the study phase and difference wave (color-consistent minus color-inconsistent) topographies

3.2.3 ERP Analysis: Retrieval Phase

Following Experiment 1, we conducted 2 (color-name consistency: consistent vs. inconsistent) × 2 (novelty: new vs. old) × 4 (brain region: frontal, frontocentral, centroparietal, parietal) repeated-measures ANOVAs for the 300-500 ms and 500-800 ms time windows (see [Figure 9: see original paper]).

(1) FN400 Old/New Effect Analysis (300-500 ms)

In the 300-500 ms window, the main effect of novelty was significant [F(1,24) = 25.57, $p < 0.001$, $^2 = 0.52$], with old names eliciting more positive amplitudes than new names. The main effect of color consistency was marginally significant [F(1,24) = 4.26, p = 0.05, $^2 = 0.15$], with color-inconsistent names eliciting more negative amplitudes. The main effect of brain region was significant [F(3,72) =

24.39, $p < 0.001$, $^2 = 0.50$], with more negative amplitudes at frontal and frontocentral regions than at centroparietal and parietal regions (ps < 0.01). The three-way interaction was significant [$F(3,72) = 6.56$, $p = 0.001$, $^2 = 0.22$]. Further simple effects analysis revealed that at frontal sites, the interaction between novelty and color consistency was significant [$F(1,24) = 6.07$, $p = 0.021$, $^2 = 0.22$]; under color-consistent conditions, old names elicited significantly larger amplitudes than new names [$F(1,24) = 25.62$, $p < 0.001$, $^2 = 0.52$], showing an old/new effect; under color-inconsistent conditions, the difference between old and new names was marginally significant [$F(1,24) = 3.66$, $p = 0.062$, $^2 = 0.13$], with old names eliciting more positive amplitudes. At frontocentral sites, the interaction between novelty and color consistency was significant [$F(1,24) = 7.51$, $p = 0.011$, $^2 = 0.24$]; both color-consistent and inconsistent conditions showed old name amplitudes larger than new names [$F(1,24) = 24.03$, $p < 0.001$, $^2 = 0.50$; $F(1,24) = 4.89$, $p = 0.037$, $^2 = 0.17$]. At centroparietal and parietal sites, novelty effects were observed [$F(1,24) = 24.29$, $p < 0.001$, $^2 = 0.50$; $F(1,24) = 27.51$, $p < 0.001$, $^2 = 0.53$], with old names eliciting more positive amplitudes. No other effects were significant.

Since significant old/new effects occurred under both color-consistent and inconsistent conditions, we calculated difference waves (old minus new) as dependent variables for a 2 (color-name consistency) × 4 (brain region) ANOVA. The interaction between color consistency and brain region was significant [$F(3,72) = 6.56$, $p = 0.001$, $^2 = 0.22$]. Simple effects analysis revealed that at frontal and frontocentral regions, the old/new effect for color-consistent names was significantly larger than for color-inconsistent names [$F(1,24) = 6.07$, $p = 0.021$, $^2 = 0.20$; $F(1,24) = 7.51$, $p = 0.011$, $^2 = 0.24$]. These results indicate that color-consistent names elicited larger FN400 old/new effects at frontal and frontocentral regions, reflecting greater item familiarity.

(2) LPC Old/New Effect Analysis (500-800 ms)

In the 500-800 ms window, the main effect of novelty was significant [$F(1,24) = 6.71$, $p = 0.016$, $^2 = 0.22$], with old names eliciting more positive amplitudes. The main effect of color consistency was significant [$F(1,24) = 7.42$, $p = 0.012$, $^2 = 0.24$], with color-inconsistent names eliciting more negative amplitudes. The main effect of brain region was significant [$F(3,72) = 15.95$, $p < 0.001$, $^2 = 0.40$], with more negative amplitudes at frontal and frontocentral regions than at centroparietal and parietal regions (ps < 0.01). The interaction between novelty and color consistency was significant [$F(1,24) = 5.35$, $p = 0.03$, $^2 = 0.18$]. Simple effects analysis revealed that for color-consistent names, old names elicited more positive amplitudes [$F(1,24) = 18.10$, $p < 0.001$, $^2 = 0.438$]. For color-inconsistent names, no significant difference emerged between old and new names. No other effects were significant. Difference wave analysis (old minus new) revealed that the old/new effect for color-consistent names was significantly larger than for color-inconsistent names [$F(1,24) = 5.35$, $p = 0.030$, $^2 = 0.18$]. Thus, color-consistent names elicited larger LPC old/new effects, indicating that more cue information was activated and participants engaged in richer detailed recollection.

[**Figure 9: see original paper**] Old/new effects under different color consistency conditions during the retrieval phase and old/new effect (old minus new) topographies

3.3 Discussion

Unlike Experiment 1, Experiment 2's color consistency judgment task during the study phase showed higher accuracy for color-inconsistent names. In Experiment 2, object name color was presented visually, while object names activated semantic representations of different object features (Collins & Loftus, 1975). Comparing the visually formed color representation with the natural color knowledge (semantic representation) activated by object names required more transformation (Kelter et al., 1984), consuming more resources. This was reflected in response times during Experiment 2's study phase that were substantially longer than in Experiment 1 (average difference = 97 ms). Additionally, because object color representations in memory have multiplicity (Vurro et al., 2013)—the same object may have multiple typical colors (e.g., bananas can be yellow or green, but rarely purple)—negative judgments of purple "bananas" are more certain than affirmative judgments of green (or yellow) "bananas." Furthermore, Lupyan (2015) proposed that when input precision is high, surface color influences mental representation more bottom-up; conversely, mental representation is more influenced by color knowledge. Thus, object mental representations in Experiment 1 were more influenced by surface color, while those in Experiment 2 were more influenced by color knowledge. This led to better discrimination performance for inconsistent than consistent items in terms of accuracy. On the other hand, because word processing can more rapidly activate object typical color semantic knowledge and mental representations (Huettig & Altmann, 2011; Naor et al., 2003), interference from conflicts between perceptual color and long-term memory color is reduced, resulting in no significant difference in response times between color-consistent and inconsistent names.

During the recognition phase, old names with color-consistent fonts showed better response times and accuracy than color-inconsistent old names; however, color-inconsistent new names showed faster response times and higher accuracy. Research (Brodeur, O'Sullivan, & Crone, 2017) indicates that color-consistent objects induce a sense of familiarity, leading individuals to judge they have "seen" the object, thereby interfering with memory and reducing accuracy. Because typical color is closely associated with object names, participants felt familiar when encountering new color-consistent names, increasing judgment difficulty and reducing accuracy. During 300-500 ms, traditional FN400 old/new effects appeared across all brain regions, with old names eliciting more positive amplitudes than new names. However, at frontal and frontocentral regions, the old/new effect for color-consistent names was significantly larger than for color-inconsistent names, indicating greater familiarity for color-consistent names. During 500-800 ms, the old/new effect for color-consistent names was significantly larger than for color-inconsistent names, indicating that participants engaged in more detailed recollection for color-consistent names, facilitating item recognition.

General Discussion

4.1 Different Effects of Color on Perceptual and Semantic Processing

Experiment 1's color judgment task during the study phase showed that color-consistent pictures yielded better response times and accuracy than color-inconsistent pictures, consistent with Vernon and Lloyd-Jones (2003). As an important object attribute, when the visually presented color matches the object's typical color, perceptual input information aligns with the established shape-color representation in long-term memory, resulting in faster and more accurate responses. Conversely, when they mismatch, object identification and color judgment are hindered. This may occur because color and shape are processed interactively and in parallel when we see an object, combining to form a unified representation (Bramão et al., 2012), with processing primarily based on visual representation. According to the spreading activation theory of memory (Collins & Loftus, 1975), object names in Experiment 2 activated semantic representations of different object features, while object name color was presented visually. Due to differences in encoding methods and the multiplicity of object color representations in memory (Vurro et al., 2013), more errors occurred when judging color-consistent object names, while color-inconsistent names with larger color differences allowed more definite judgments.

ERP results further showed that during the study phase, color consistency effects on N400 emerged only in Experiment 1, with color-inconsistent pictures eliciting more negative ERP amplitudes than consistent pictures. Neither P600 in Experiment 1 nor N400 and P600 in Experiment 2 showed clear color consistency effects. Object picture identification (Experiment 1) resembles the influence of picture context effects on object discrimination (300-500 ms) (Ganis & Kutas, 2003) and atypical color object identification (N350) (Bramão, Faísca et al., 2011), reflecting that item-context inconsistency modulated N400 during encoding (Guillaume, Baier, & Etienne, 2020). Learning object names (Experiment 2) resembles real-time mental simulation of implied object color information during Chinese sentence comprehension (Li & Shang, 2017); the process of matching object names to long-term memory object feature representations with current visual color is more complex (prolonged response times), reducing the facilitative effect of visual color. In summary, according to Schendan and Kutas's (2002, 2003) division of object recognition into early (N350 or N400) and late (P600) stages, color semantic conceptual representation in object picture identification occurs primarily during the early stage (N400), whereas color semantic representation in object name judgment is not affected by visual color.

4.2 The Relationship Between Object Color and Shape/Semantic Representation

Object storage and representation in memory systems are flexible and complex. During early visual processing, color information is processed and bound in parallel with other surface features (e.g., shape, texture), jointly influencing internal visual object representation (Ding & Lin, 2000; Ding, Wang, & Guo, 2004). These features are stored separately in long-term memory, along with associations formed between them in episodic memory (Brady, Konkle, Alvarez, & Oliva, 2013; Brady, Störmer, & Alvarez, 2016; Ding & Lin, 2001). Retrieval depends on interactions between encoding, information features, and stimulus context (Leynes & Crawford, 2018). Therefore, memory retrieval involves combined extraction of feature and association information. Regarding this study, color's influence on object recognition is manifested through representations combining color and shape in some manner. To some extent, the object representation system can bind arbitrary perceptual information together to form new object representations, rather than relying solely on external features. This binding ability is present by 8-10 months of age (Oakes, Baumgartner, Kanjlia, & Luck, 2017) and does not decline with age (Read, Rogers, & Wilson, 2016). Both shape-color associations stored in long-term memory and temporarily input shape-color associations during perception jointly influence episodic memory retrieval. Factors promoting recognition of color-consistent old pictures may be twofold: reliance on existing shape-color representations in long-term memory, and newly formed shape-color associations during the study phase. Recognition of color-inconsistent old pictures has only one facilitative factor—newly formed shape-color associations during the study phase—while also experiencing interference from retrieving established strong associations. Therefore, the former yields better performance than the latter, consistent with previous research (Lloyd-Jones & Nakabayashi, 2009; Nagai & Yokosawa, 2003; Vernon & Lloyd-Jones, 2003).

Regarding color consistency, color-consistent binding is permanent, while inconsistent binding is temporary. For object pictures and names, picture processing is more visual-based, while name processing is more semantic-based. In Experiments 1 and 2, the binding strength between color knowledge and other object information differs; moreover, binding different object features requires attentional resources (Allen, Hitch, Mate, & Baddeley, 2012; Baddeley, 2002; Zokaei, Heider, & Husain, 2014; Fu, 2019). Therefore, representing color consistency for object pictures and names involves different types of processing: one automatically processes specific perceptual memory representations (pictures), while the other processes abstract, generalized memory representations (names). Küper and Zimmer (2018) propose that these two processing types can modulate both recollection and familiarity, and more importantly, they reflect the type of information prioritized and corresponding processing preferences during episodic memory retrieval. In this study's encoding phase, object color facilitated picture identification but inhibited object name judgment. During retrieval, color's facilitative effect on picture recognition manifested in familiarity (FN400), while its effect on names reflected in recollection (LPC). This indicates that color has different effects on perceptual and semantic processing, producing different retrieval patterns. Although color was input visually in both perceptual and conceptual processing, its mode of action differed between the two, affecting not only the encoding process (study phase) but also subsequent retrieval (test phase) differently. For encoding, the difference lies in whether representation transformation occurs (conceptual processing) or not (perceptual processing). During recognition retrieval, color knowledge at the perceptual level influences familiarity more than at the semantic level; conversely, recollection is more affected by semantic level processing. Similar to Guillaume et al.'s (2020) finding that item-scene consistency effects appeared in both early encoding and late retrieval ERP old/new effects, this study's item-color consistency effects also influenced both encoding and retrieval.

4.3 Object Color Facilitates Recognition Retrieval

High color diagnosticity of objects influences not only object discrimination at the perceptual level but also information retrieval from long-term memory. In this study's recognition tasks, both color-consistent object pictures and names showed better recognition performance than color-inconsistent ones. Shape-color associations stored in long-term memory facilitated information retrieval for color-consistent items while interfering with retrieval of color-inconsistent items. This further demonstrates that color changes significantly affect overall recognition memory performance, with consistent items showing higher recognition accuracy than inconsistent items (Cui et al., 2016).

Both experiments showed FN400 old/new effects during the retrieval phase, indicating that the memory system generated familiarity judgments for both color-consistent and inconsistent items. Because inherent features of objects are processed automatically during object identification, influencing familiarity (Ecker et al., 2007), and familiarity can facilitate source recognition, especially when source information is encoded as item detail (Diana, Van den Boom, Yonelinas, & Ranganath, 2011), early processing during recognition retrieval (color) is a more automatic process. Additionally, Cycowicz et al. (2008) found that recognition differences between color-consistent and inconsistent items also occurred in late (500-600 ms) ERP components. The LPC recollection components differed slightly between object picture and name retrieval in this study. Experiment 1 showed no color consistency effect, and LPC old/new effects appeared only under color-inconsistent conditions; Experiment 2 showed clear color consistency and old/new effects, with larger LPC recollection components during recognition. This may reflect differences in processing objects between the two experiments: Experiment 1 involved low-level graphic processing, while Experiment 2 involved high-level semantic processing, with different influences from color knowledge stored in long-term memory in semantic form. In high-level processing, color is stored as part of semantic representation in the object's knowledge framework; when activated, it forms a visual representation that promotes memory representation for object names. According to the spreading activation model (Collins & Loftus, 1975), concepts with strong semantic connections have higher activation strength and greater spread. In this study, the connection strength between consistent color and object name was higher than between inconsistent color and object name, producing greater activation that facilitated memory for color-consistent names, resulting in better recognition performance than for color-inconsistent names.

Multiple memory systems theory (Schacter & Cooper, 1992) divides memory into a structural description system and an episodic memory system. The structural description system processes and represents object structure information in the visual field without representing visual components such as object size and color, affecting implicit memory tasks; the episodic memory system encodes and represents semantic and visual information about objects, relating to explicit memory tasks. These two memory systems often influence each other. In this study, color's role in object recognition memory includes both low-level and high-level processing. In low-level processing, color helps the visual system identify and recognize objects quickly and efficiently, similar to priming effects in implicit memory. In high-level processing, color is stored as part of semantic representation in the object's knowledge framework; when activated, it is represented in the visual system like perceptual information, which in turn promotes memory representation and retrieval. In summary, through mutual influence between the structural description system and episodic memory system, color facilitates recognition retrieval in both low-level and high-level processing, specifically manifested as accurate colors enhancing scene recognition memory, while incorrectly colored pictures show no memory advantage (Wichmann, Sharpe, & Gegenfurtner, 2002).

Conclusion

The results demonstrate that color influences both encoding and retrieval of object episodic memory, specifically: (1) Color has different effects on item encoding at perceptual and semantic levels, facilitating object discrimination at the perceptual level while hindering it at the semantic level. (2) Color congruence promotes familiarity and recollection in object picture retrieval (perceptual level) but facilitates only recollection in object name retrieval (conceptual level). (3) The consistency effect during object name recognition indicates that color is closely related to object names and similarly affects semantic representation of objects, further supporting the spreading activation model.

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Note: Figure translations are in progress. See original paper for figures.