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Integration of perceptual information in word access

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Abstract

According to experiential theories of language comprehension, perceptual information plays an essential role when word meanings are accessed. We conducted four experiments to investigate how different types of perceptual information such as color and shape are combined during word access. One possibility is that the color and shape of a word's referent are activated independently from one another and combined in an additive manner. Alternatively, words might activate perceptual representations via a multiplicative integration of color and shape. Experiment 1 established that participants follow a multiplicative similarity rule when they judge the similarity of schematic pictures to actual fruits and vegetables. In Experiments 2 to 4, participants performed a classification task, a lexical decision task, or a word naming task on names of fruits and vegetables that were superimposed on a background picture. Responses were facilitated only when both color and shape of the picture matched the word's referents. Response times were associated positively with mean similarity ratings and the consistency of these ratings obtained in the first experiment. These results suggest a multiplicative integration of different types of perceptual information during word access.

Key words: color, perceptual representations, language comprehension, shape, word meanings

Integration of perceptual information in word access

Experiential theories of language comprehension have emerged in reaction to fundamental explanatory problems in the classical amodal approach to language comprehension and semantic memory (e.g., Barsalou, 1999; Glenberg & Kaschak, 2002; MacWhinney, 1999; Zwaan, 2004). The most serious of these problems is the symbol-grounding problem (Harnad, 1990). Theories that rely on amodal representational formats such as propositions (e.g., Kintsch, 1988), schemata (Rumelhart, 1980), or vector representations (Landauer & Dumais, 1997) are unable to explain how mental representations refer to objects and events in the world and how these representations are grounded in perception and action. Experiential theories attempt to close this explanatory gap by starting from the assumption that the representations involved in language comprehension are of the same kind as the representations involved in sensory experiences, perceptions, and actions.

By now, there is a multitude of experiments that substantiate this general claim by demonstrating that perceptual information such as shape, color, orientation, or movement is routinely activated in language comprehension (see Zwaan, 2004, for an overview). In addition, there is evidence that processing motion sentences affects perception (Zwaan, Madden, Yaxley, & Aveyard, 2004) and that incidentally processing motion words influences motion perception (Meteyard, Bahrami, & Viglioccio, 2007). However, all of the experiments conducted so far concentrated on one particular perceptual dimension at a time. As a consequence, little is known about how several types of perceptual information are integrated during language comprehension when comprehenders form perceptual representations of the objects and events described in words, phrases, and sentences. The present experiments addressed this question for the most basic case of language comprehension, the access to word meanings. More specifically, we investigated how comprehenders utilize color and shape information simultaneously when they process nouns that refer to color-diagnostic objects (Tanaka, Weiskopf, & Williams, 2001).

In the following sections, we will start by reviewing previous studies on the roles that shape and color information alone can play in language comprehension. We will then suggest that color and shape information might be combined either in an additive or in a multiplicative way during the comprehension of words that require integrating both types of perceptual information into one perceptual simulation. The idea of an additive combination of different types of perceptual information is related to independent cue models whereas the idea of a multiplicative combination is borrowed from non-linear cue integration models developed in the categorization literature. In principle, both theoretical alternatives are compatible with an experiential view of language comprehension but they make different predictions as to how perceptual processes interact with language comprehension. The experiments reported here tested some of these predictions with a priming paradigm in which schematic visual stimuli with varying shapes and colors were combined with different language processing tasks.

The Role of Shape and Color Information in Language Comprehension

Shape is a major cue in object recognition (e.g. Biederman, 1987). For this reason, experiential theories of language comprehension would predict that shape information also plays an important role in the comprehension of linguistic expressions that refer to concrete objects. There is evidence from different lines of research supporting this hypothesis. Indirect support comes from experiments on the relationship of picture and word processing (Glaser, 1992). The picture stimuli used in typical experiments of this kind are schematic line drawings that primarily convey shape information (e.g., the widely used line drawings normed by Snodgrass & Vanderwart, 1980). In priming experiments in which words and schematic line drawings were presented in close succession, facilitative effects have been observed in both directions; picture processing was primed by semantically related words and word processing was primed by semantically related pictures (e.g., Carr, McCauley, Sperber, & Parmelee, 1982; Sperber, McCauley, Ragain, & Weil, 1979; Vanderwart, 1984). Such cross-form priming effects have been obtained for a variety of tasks such as naming, categorization, and lexical decision, in particular under conditions that stimulated semantic processing of the word stimuli (Bajo, 1988). Large facilitatory effects of matching pictures on word processing have been found in tasks that require relatively deep semantic processing (such as categorization, Durso & Johnson, 1980; Glaser & Düngelhoff, 1984; Irwin & Lupker, 1983). Although such effects are usually not explained with reference to experiential representations, they fit naturally with the view that the comprehension of words as well as pictures is based on the same perceptual representations. More direct evidence for the activation of shape information in language comprehension is provided by research within the context of experiential theories. In an experiment by Zwaan, Stanfield, and Yaxley (2002), for example, individuals were faster to recognize the picture of an object or animal when the picture matched the shape of the object implied by the sentence content (e.g., the picture of an eagle with its wings outstretched vs. folded after reading *The ranger saw the eagle in the sky*). A parallel effect was found for the more indirect task of picture naming, indicating that shape information is routinely activated in sentence comprehension (see also Holt & Beilock, 2006; Lincoln, Long, & Baynes, in press).

Compared to shape, the role of color information in language processing has attracted relatively little systematic research. However, parts of the literature on the Stroop effect (Stroop, 1935) suggest that color information is activated in the processing of words that refer to color-diagnostic objects. Following a pioneering study by Klein (1964), a number of experiments have demonstrated that not only color words, but also color-related words such as *blood*, *snow*, or *sky* produce interference, with stronger interference effects for words that are more color-diagnostic (Scheibe, Shaver, & Carrier, 1967). In addition, interference effects of color-related words have been observed across response modalities, if the color-related word is unrelated to the colors in the response set (Risko, Schmidt, & Besner, 2006) and if the ink color and the color implied by the color-related word differ from each other but require the same response (Schmidt & Cheesman, 2005). In all of these cases, the common explanation of the Stroop effect in terms of response conflicts cannot be applied. Rather, an explanation in terms of stimulus conflicts seems more plausible: Words referring to color-diagnostic objects might activate color information which, in turn, interferes with processing the to-be-named color. Despite the fact that it has not developed within the experiential framework, the idea that certain variants of the Stroop effect are due to stimulus conflicts is very close to the hypothesis of a routine activation of color representations in language comprehension. Recent experiments by Richter and Zwaan (2008) tested this hypothesis directly. In these experiments, processing of color words interfered with perceptual judgments in a color discrimination task when the color word and the target color were incongruent. This finding provides direct evidence for the claim of that meaning representations of words can include color information in a modal format as well.

Integration of Shape and Color Information in Word Access: Theoretical Accounts

The previous section has shown that various sources provide direct or indirect support for the core assumption of experiential theories that perceptual information plays a major role in language comprehension. In particular, shape as well as color information is activated in the comprehension of words if these words refer to objects that are typically recognized on the basis of their shape and color. But how are color and shape integrated to form a perceptual representation of the word's referent? There are two basic theoretical options to describe this process, an additive combination of independently represented features and a multiplicative combination of cues into an integrated representation of a word's referent. In principle, both options are compatible with experiential theories of language comprehension. The two options will be discussed in turn.

Additive Combination of Generic Representations of Color and Shape

According to one possibility, color and shape information are activated independently from one another and additively combined to form an integrated perceptual representation of the word's referent (*additive combination view*). Upon encountering the word *tomato*, for example, comprehenders would activate generic perceptual representations of a red color and a round shape. These generic representations would then be combined to construct a perceptual representation of the word's referent, i.e. a red and round tomato. The idea that perceptual representations of word meanings rely on an additive combination of generic representations of properties bears resemblance to central assumptions of schema-theory (Rumelhart, 1980) and of independent cue models of categorization (e.g., Reed, 1972). Both types of models endorse the assumption that concepts can be described as a set of independent features that are combined in an additive fashion. In independent cue models of classification, for instance, category membership is determined by a linear additive combination of separate features (see Murphy, 2002, for an overview). Models that assume linear additive combination are still being used in research on categorization and the related topic of multiple cue judgment (e.g., Ell & Ashby, 2006; Juslin, Karlsson, and Ollson, 2008; Juslin, Olsson, & Olsson, 2003). In his theory of perceptual symbol systems, Barsalou (1999) has demonstrated how the notion of perceptual representations can be combined with the notions of schemata and compositionality. Thus, schematic representations of generic shapes and colors (e.g., representations of round and red) can be combined to represent specific objects (e.g., a tomato). It seems straightforward to assume that these representations are additively combined when a perceptual simulation of a word's referent is constructed.

The predictions of the additive combination view can be tested with cross-form priming experiments in which words with color diagnostic referents are primed by visual stimuli that match or mismatch the words' referents in color and shape. For this paradigm, the additive combination view implies that the processing of the verbal stimulus should be facilitated if any of the schematic perceptual representations that are used in the perceptual simulation of the word's referent have already been activated. Perceiving a colored shape (e.g., a red round shape) activates a schematic color representation (e.g., a generic representation of red) and a schematic shape representation (e.g., a generic representation of a round shape). Likewise, when participants process a word referring to a color diagnostic object, they engage in a perceptual simulation of its referent that makes use of schematic color and shape representations as well. The more schematic components needed for this simulation are already activated as a result of processing the visual stimulus, the easier it should be to carry out the perceptual simulation. As a consequence, the additive combination view implies that the priming effects of color and shape on processing the name of a color-diagnostic object should also be additive.

Multiplicative Integration of Color and Shape

A second and contrasting theoretical possibility is that color and shape information are integrated in a non-linear, multiplicative manner when a noun denoting a color-diagnostic object is processed (*multiplicative integration view*). The perceptual representation that is activated by the word *tomato*, for example, might be based on an object representation that is formed by an interactive integration of both a red color and a round shape rather than an additive combination of separate representations of red and round. The implications of such a view are similar to certain assumptions of interactive cue models of categorization such as the context model (e.g., Medin & Schaffer, 1978) and its derivatives (Kruschke, 1992; Nosofsky, 1984, 1986). According to these models, category membership is determined by a non-linear combination of matching and mismatching features. One important implication of a non-linear (e.g., multiplicative) integration of features is that the effects of two matching features (e.g., color and shape) is greater than their independent effects.

For cross-form priming experiments with visual priming stimuli whose colors and shapes match or mismatch the referent of the target word, the multiplicative integration view makes predictions that are at variance with those of the additive combination view. Given that both color and shape are essential for recognizing color-diagnostic objects, perceptual representations of these objects are likely to entail both a certain color and a certain shape. It seems plausible to assume that the amount of priming that these representations receive from a visual stimulus depends on their psychological similarity to the stimulus. If this similarity rule is non-linear (e.g., multiplicative), as the multiplicative integration view entails, perceiving a colored shape that matches the object representation only in color or in shape should cause a small priming effect at best. However, perceiving a colored shape that matches the object representation in color as well as in shape should cause a strong priming effect on the processing of the object name. This priming effect should be greater than the sum of priming effects caused by color or shape alone because the similarity between the priming stimulus and the object representation that is activated during word access is much higher when two features match rather than one.

The predictions of the multiplicative integration view can also be framed in terms of Sternberg's (1969) additive factors logic. According to Sternberg, interactive effects of two independent variables (e.g., stimulus or task features) indicate that the processes evoked by these variables influence each other because they are located at the same stage of processing. This is what the multiplicative integration view predicts for the effects of color and shape on processing of words.

Rationale of the Present Experiments

We conducted four consecutive experiments to test whether word access involves an additive combination of independently activated perceptual features (additive combination view), or whether it involves perceptual representations of referent objects that are based on a multiplicative integration of perceptual features (multiplicative integration view). In Experiment 1, words were presented together with visual stimuli that either matched or mismatched the typical color or shape of the word's referent, and participants rated the similarity of these stimuli to the words' referents. The primary goal of this experiment was to lay the foundation for the subsequent experiments by establishing whether individuals followed an additive similarity rule (consistent with the additive combination view) or a multiplicative similarity rule (consistent with the multiplicative integration view) in providing similarity ratings for the stimuli that were also used in Experiments 2 to 4.

Experiments 2 to 4 used a priming paradigm in which the visual stimuli pilot-tested in Experiment 1 served as primes, and the verbal stimuli served as targets. The idea here is that shapes and colors or shape-color combinations overlap with experiential traces (e.g., those of having seen fruits and vegetables). Because these experiential traces are linked with lexical representations (e.g., through Hebbian learning), activation of experiential traces will prime lexical representations (Pulvermüller, 1999; Zwaan, 2004). The multiplicative integration view predicts a large priming effect for stimuli that matched the referents in both color and shape but a small or non-existent priming effect for stimuli that match the referents only in color or in shape. Experiments 2 to 4 differed in the amount of attention to semantic processing required by the task that participants performed on the verbal stimuli (for a computational model of task-dependent attention to semantic processing, cf. Mirman, McClelland, Holt, & Magnuson, 2008). The tasks used were a classification task in Experiment 2, a lexical decision task in Experiment 3, and a word naming task in Experiment 4. The classification of verbal stimuli into different categories is a task that clearly requires semantic processing (e.g., Bajo, 1988). In contrast to classification decisions, lexical decisions can in principle be made on the basis of orthographic information alone. Nevertheless, the ease of lexical decision is usually affected by the semantic features of words at least to some extent as shown by large-scale regression analyses (Balota, Cortese, Sergent-Marshall, Spieler, & Yap, 2004; see also Chumbley & Balota, 1984). For word naming latencies, Balota et al. (2004) found effects for semantic variables that were smaller compared to the lexical decision latencies. Thus, despite the fact that word naming is a phonological task, comprehenders still seem to pay some attention to semantic processing (cf. also Strain, Patterson, & Seidenberg, 1995).

The purpose of using three tasks that differed in the amount of attention to semantic processing was twofold. First, it allowed a test of the generalizability of the two alternative views on the integration of perceptual information during word access. In particular, we were able to investigate whether the predictions of the additive combination view or the multiplicative integration view hold even for tasks such as lexical decision and word naming that require relatively little attention to semantic processing. Second, if perceptual representations are indeed critical for semantic processing as experiential theories of language comprehension suggest, the magnitude of the effects predicted by either the additive combination or the multiplicative integration view may be expected to decrease from the task that involves a relatively deep level of semantic processing to the task that involves a relatively shallow level of semantic processing.

Experiment 1

In all experiments reported in this article, we used names of fruits and vegetables with typical colors and shapes as words referring to color-diagnostic objects. In Experiments 2 to 4, these words were presented together with schematic background pictures that either matched or mismatched the color or shape of the fruit or vegetable denoted by the word. Experiment 1 laid the foundation for these experiments by following two related aims. The first aim was to establish whether individuals apply an additive or a multiplicative similarity rule when judging the similarity of the visual stimuli to actual referents of the verbal stimuli. For these judgments, the additive combination view implies that individuals use color and shape as independent cues when providing their similarity judgments. In contrast, the multiplicative integration view entails that color and shape do not contribute to the perceived similarity of visual stimulus and the word's referent in a completely independent manner. Rather, if a multiplicative similarity rule is operative that resembles the one embedded in interactive cue models (e.g., Medin & Schaffer, 1978), color and shape information should interact. The second aim of Experiment 1 was to collect normative similarity ratings for different combinations of verbal and visual stimuli. Later on, these similarity ratings were used to predict the magnitude of priming effects obtained in Experiments 2 to 4.

Method

Participants. Participants were 21 psychology undergraduates.

Stimulus materials. Experiment 1 included verbal and visual stimuli. Verbal stimuli were names of ten fruits and ten vegetables with typical colors and shapes (e.g., tomato, tangerine) that were selected on the basis of two norming studies. In the first norming study, 24 psychology undergraduates (different from the experimental samples) were given a questionnaire with the names of 54 fruits and vegetables. For each of these names, participants were asked to indicate whether they knew the fruit or vegetable, to specify up to two typical colors, and to rate the typicality of the specified color(s) on a 6-point rating scale (from 1=*weakly typical* to 6=*highly typical*). In the second norming study, 15 psychology undergraduates received a questionnaire with the same 54 names of fruits and vegetables. They were asked to specify the typical shape of each fruit and vegetable on a 9-point scale from -4 (labeled *round* and illustrated by a schematic round shape) to +4 (labeled *elongated* and illustrated by an elongated shape), with a middle category (labeled *oval* and illustrated by an oval shape). As experimental stimuli, we selected those fruits and vegetables (a) for which the participants of the first norming study consistently mentioned one particular color (proportion of mentions: M = .95, SD = 0.07) and rated this color as highly typical (M = 5.61, SD = 0.16) and (b) which the participants of the second norming study consistently rated as either having a round shape (M = -3.00, SD = 0.82) or an elongated shape (M = 3.14, SD = 1.18; see Appendix A for a list of experimental verbal stimuli). Visual stimuli were schematic pictures of two-dimensional shapes that were either round (5.1 cm in diameter) or elongated (10.0 cm in length and 2.0 cm in height) with rounded ends and a horizontal orientation. In addition, the visual stimuli differed in color (green, red, yellow, orange, purple). It is important to note that due to their schematic nature, the visual stimuli did not correspond to any particular fruit or vegetable (see http://www.allg-psych.uni-koeln.de/richter/ColorShape_SupplementaryMaterial.pdf for samples).

Procedure. Participants provided ratings of the similarity of the visual stimuli to actual fruits and vegetables denoted by the verbal stimuli for 130 different combinations of stimulus words and background pictures (all combinations that were used in Experiments 2 to 4). The combinations of words and background pictures were presented one-by-one on a computer screen. The visual stimulus was presented in the middle of the screen against a light-grey background. The stimulus words were presented in black letters (Arial, 20 pt) above the visual stimulus in a white background stripe. Participants provided their ratings via key presses on a scale from 0 (*not similar at all*) to 4 (*very similar*).

Design. The design was a 2 (color match vs. mismatch) X 2 (shape match vs. mismatch) design with repeated measurements on both independent variables.

Results

The analyses of the data from all experiments reported in this article were based on by-subjects ANOVAs (F_1) and by-items ANOVAs (F_2). All significance tests were based on an α-level of .05. Where appropriate, we report partial η^2 and Cohen's *d* as measures of effect size.

(Figure 1 about here)

An ANOVA of the similarity ratings for each combination of stimulus words and background pictures (Figure 1) revealed a strong main effect for color match vs. mismatch ($F_1(1,20) = 89.8, p < .001, \eta^2 = .82$; $F_2(1,126) = 627.1, p < .001, \eta^2 = .83$). Background pictures with colors matching the color of the fruit or vegetable denoted by the stimulus word were rated as more similar ($M_{\text{Items}} = 2.37$, $SE_{M\ \text{Items}} = 0.05$) than background pictures with mismatching colors ($M_{\text{Items}} = 0.80$, $SE_{M\ \text{Items}} = 0.04$). There was also a strong main effect for shape match vs. mismatch ($F_1(1,20) = 78.4, p < .001, \eta^2 = .80$; $F_2\ (1,126) = 395.8, p < .001, \eta^2 = .76$). Background pictures with matching shapes were rated as more similar to the actual fruit or vegetable ($M_{\text{Items}} = 2.21$, $SE_{M\ \text{Items}} = 0.05$) than background pictures with mismatching shapes ($M_{\text{Items}} = 0.96$, $SE_{M\ \text{Items}} = 0.04$). However, both main effects were qualified by an ordinal interaction effect of the two variables ($F_1(1,20) = 17.3, p < .001, \eta^2 = .46$; $F_2\ (1,126) = 19.5$, $p < .001, \eta^2 = .13$). Background pictures that matched the actual fruit or vegetable in color as well as in shape were rated as considerably more similar ($M_{\text{Items}} = 3.13$, $SE_{M\ \text{Items}} = 0.07$) than background pictures that matched only in color ($M_{\text{Items}} = 1.61$, $SE_{M\ \text{Items}} = 0.07$) or shape ($M_{\text{Items}} = 1.29$, $SE_{M\ \text{Items}} = 0.05$). Both of these differences were larger than the differences of background pictures that matched only in color or shape to background pictures that mismatched on both dimensions ($M_{\text{Items}} = 0.31$, $SE_{M\ \text{Items}} = 0.04$). These results support the idea that participants used a non-linear (multiplicative) similarity rule in computing the similarity of the visual stimuli to actual fruits and vegetables. The following three experiments addressed the question whether multiplicatively integrated perceptual representations of color and shape are also activated spontaneously when individuals process the names of fruits and vegetables.

Experiment 2

In Experiment 2, participants performed a classification task on names of fruits and vegetables. The classification responses were primed with the schematic background pictures that were introduced in the previous experiment. These pictures could either match or mismatch actual referents of the stimulus words in color or shape. Classification of verbal stimuli requires relatively deep semantic processing. Accordingly, research on picture-word processing has repeatedly demonstrated that the classification of verbal stimuli is facilitated when these stimuli are presented together with a picture that matches the word’s referent (Dell’Acqua & Grainger, 1999; Glaser & Düngelhoff, 1984). In all experiments conducted so far, however, monochrome line drawings have been used as visual stimuli, leaving the question undecided how color information and shape information are integrated.

The additive combination view and the multiplicative integration view predict different patterns of response times in the classification task. The additive combination view implies that matching color or matching shape of the visual stimulus independently facilitate the simulation of the fruit or vegetable denoted by the stimulus word. As a consequence, this view predicts additive priming effects of color and shape on the response times in the classification task. The multiplicative integration view, in contrast, assumes that a name of a fruit and vegetable activates a perceptual representation of its referent that includes both shape and color information. Accordingly, this view predicts multiplicative priming effects, i.e., an interaction of color and shape information. Classification responses should receive strong facilitation when *both* color and shape of the visual stimulus match the color and the shape of the fruit or vegetable denoted by the stimulus word. In particular, the facilitation caused by a double match of color and shape should be greater than the sum of facilitatory effects caused by color or shape alone (if there are any). For exploratory purposes, we also varied the stimulus onset asynchrony of visual and verbal stimuli in order to detect potential differences in the time course of the activation of color and shape information.

In addition to an experimental test of the predictions of the two alternative views, we conducted supplemental analyses to investigate whether and to what extent the facilitation of classification responses covaries with the perceived similarity of the visual stimulus and the word's referent. For this purpose, we predicted the individual classification latencies for each combination of visual and verbal stimuli by the means and the standard deviations of the normative similarity ratings collected in Experiment 1 for each combination of visual and verbal stimuli. Provided that a multiplicative similarity rule determines the perceived similarity of the visual stimuli to actual fruits and vegetables, the multiplicative integration view implies that the classification latencies should be negatively related to the mean similarity ratings. In addition, we assumed that the classification latencies should be positively related to the standard deviations of the similarity ratings because a high interindividual inconsistency in these ratings is likely to be caused by a greater variety in the appearance of actual fruits and vegetables. This greater variety, in turn, may diminish the average magnitude of priming effects.

Method

Participants. Eighty psychology undergraduates took part in Experiment 2. Of these, six were excluded from the analysis because they reported being myopic (self-rated severity of 5 or higher on a rating scale from 1 to 10) and not wearing corrective lenses during the experimental session. The remaining 74 participants (34 women and 40 men) had a mean age of 18.9 years (*SD* = 1.4).

Stimulus materials. As experimental verbal stimuli, we used the same pilot-tested names of ten fruits and ten vegetables with typical colors and shapes as in Experiment 1. In addition to the experimental stimuli, names of ten herbs (e.g., basil, mustard) and ten cereals (e.g., wheat, rice) were used as filler items. Twelve additional names of fruits, vegetables, herbs, and cereals served as practice items. As visual stimuli, the same set of shapes (round vs. elongated) with different colors (green, red, yellow, orange, purple) as in Experiment 1 was used.

Procedure. Participants performed a classification task on the experimental and filler items. The stimulus words were presented one-by-one on a computer screen. Participants were instructed to indicate as quickly as possible by pressing one out of four response keys whether the word on the screen was the name of a fruit, a vegetable, an herb, or a cereal. We included four response categories rather than two in order to increase the difficulty of the task and in order to be able to include a large percentage of filler trials in which the verbal stimuli bore no relationship at all to the visual stimuli presented. Participants operated the response keys with the middle and index fingers of their left and their right hand. The assignment of response keys to one of the four categories was randomized across participants, with the constraint that the two response keys corresponding to the index fingers were always assigned to the experimental stimulus categories (fruits and vegetables). The experiment started with 24 practice trials, with each practice item presented twice. During the practice trials, participants received feedback on the accuracy of their responses. The actual experiment included 40 experimental and 40 filler trials in a randomized order, with each of the experimental and filler items presented twice. In each trial, a stimulus word was printed in black letters (Arial, 20 pt) on a light-grey rectangular stripe (4.8 cm in length and 1.5 cm in height) that appeared in the center of a visual stimulus. The purpose of the light-grey rectangular stripe was to keep the readability of the stimulus words constant regardless of the color of the background picture. The viewing distance was approximately 45 cm. Background picture and stimulus word remained on the screen until participants responded. Between trials, there was a 1500 ms break followed by a fixation cross that was presented for 300 ms in the middle of the screen. After the actual experiment, an object recognition task was given in order to check whether participants knew what the fruits and vegetables denoted by the experimental stimulus words looked like. For the object recognition task, the 20 experimental stimulus words were presented twice, once together with a picture of the fruit or vegetable denoted by the word (e.g., the word *plum* together with a picture of a plum) and once with the picture of a different fruit or vegetable that was not part of the set of experimental items (e.g., the word *plum* together with a picture of a pear). The participants' task was to decide whether the picture showed the fruit or vegetable denoted by the word. The object recognition trials were presented in random order.

Design. In eight of the experimental trials, the color and shape of the background picture matched the typical color and shape of the fruit or vegetable denoted by the stimulus word, in eight experimental trials color matched and shape did not match, in eight experimental trials color did not match and shape matched, and in eight experimental trials neither color nor shape matched. In eight further experimental trials, the stimulus word was presented in the center of a grey square (neutral background picture). For one group of participants, the onset of the background picture preceded that of the stimulus word by 200 ms whereas for a second group, stimulus word and background picture were presented simultaneously. Accordingly, the design was a 2 (color match vs. mismatch) X 2 (shape match vs. mismatch) X 2 (stimulus onset asynchrony (SOA): 0 ms vs. 200 ms) design, with the first two factors varying within participants and the third factor varying between participants. The neutral condition was used to determine the relative inhibition or facilitation of classification in the experimental conditions. For each participant, each experimental item was presented in two different experimental conditions or in one experimental condition and the neutral condition. The assignment of experimental items to experimental conditions and the neutral condition was counterbalanced between participants on the basis of 10 different stimulus lists. Filler items and background pictures were combined in a random manner, with the constraint that each background picture was presented equally often with experimental items on the one hand and filler items on the other hand.

Results and Discussion

In addition to by-subjects and by-items ANOVAs for testing main and interaction effects of color match and shape match, we tested facilitation effects directly by comparing experimental conditions with the neutral condition. For the supplemental analyses of the relationship of classification latencies and the similarities of background pictures to actual fruits and vegetables, we used multilevel models with random coefficients.

The relatively large sample size in Experiment 2 was chosen in order to ensure that power for testing effects involving the between-subjects manipulation of SOA was high in the by-subjects analyses. With the actual sample size of 74 participants, the power for tests of interactions of SOA with color match/mismatch or shape mismatch was .99 under the assumptions of a medium-sized effect ($f = .25$ according to Cohen, 1988), a type-I error probability of .05 and substantial correlations ($\rho = .75$) between the levels of the within-subjects factors (power analyses were performed with the software GPower; Faul, Erdfelder, Lang, & Buchner, 2007). For the hypothesis-relevant tests involving only the within-subjects factors, power was even higher.

Classification and object identification accuracy. Overall, the accuracy of the classification responses for the experimental stimuli was consistently high ($M = .91$, $SD = .06$; see Appendix B for accuracy data by experimental conditions). An ANOVA performed on the arcsine-transformed proportions of correct classifications revealed no systematic effects of color match vs. mismatch or shape match vs. mismatch (for all effects: $F(1,72) < 2.5$, $p > .12$). For this reason, it is unlikely that the effects on response latencies reported below are due to a speedaccuracy trade-off. In the object recognition task provided after the experiment, participants were able to identify the fruits and vegetables denoted by the experimental stimulus words with a consistently high accuracy (proportion of correctly identified fruits and vegetables: $M = .96$, $SD = .04$).

Response latencies. Response latencies for the experimental trials with correct responses were inspected for outliers. Latencies deviating more than two standard deviations from the condition mean (3.5% of all latencies) were eliminated. The grand mean of the adjusted response latencies was 1029 ($SD = 146$). The condition means are provided in Appendix C. In an ANOVA performed on the adjusted response latencies, there was no significant main effect of shape match vs. mismatch ($F_1(1,72) = 0.3$, $p = .60$; $F_2(1,38) = 0.2$, $p = .65$) but a significant main effect of color match vs. mismatch ($F_1(1,72) = 7.4$, $p < .01$, $\eta^2 = .09$; $F_2(1,38) = 5.6$, $p <.05$, $\eta^2 = .13$). However, this effect was qualified by an ordinal interaction of color match vs. mismatch and shape match vs. mismatch that was significant in the by-subjects analysis ($F_1(1,72) = 5.0$, $p < .05$, $\eta^2 = .07$) but failed to reach significance in the by-items analysis ($F_2(1,38) =2.6$, $p = .11$, $\eta^2 = .06$; Figure 2a). Only if the background shape also matched the fruit or vegetable denoted by the stimulus word, were responses in the color match condition faster ($M = 984$ ms, $SE_M = 20$) than responses in the color mismatch condition ($M = 1067$ ms, $SE_M = 23$; $p < .05$ in the by-subjects and the by-items analyses). When the background shape did not match, however, responses in the color match condition did not differ from those in the color mismatch condition ($p > .63$). Stimulus onset asynchrony did not have a main effect on the response latencies, nor did it interact with any of the other independent variables (for all effects: $F_1(1,72) < 2.3$, $p > .13$; $F_2(1,38) < 0.8$, $p > .38$).

(Figure 2 about here)

Compared to the neutral condition, classification decisions were faster when both the color and the shape of the background picture matched the actual color and shape of the fruit or vegetable denoted by the stimulus word ($t_{\text{Subjects}}(73) = -3.2$, $p < .01$, $d = 0.37$; $t_{\text{Items}}(39) = -2.9$, $p < .01$, $d = 0.46$). Neither color match nor shape match alone, in contrast, were sufficient to yield classification decisions that differed significantly from those in the neutral condition (for both comparisons: $|t|_{\text{Subjects}}(73) < 1.1$, $p > .26$, $d < 0.14$; $|t|_{\text{Items}}(39) < 1.1$, $p > .28$, $d < 0.17$). Likewise, there was no facilitation effect when both color and shape were mismatching ($|t|_{\text{Subjects}}(73) < -0.3$, $p > .73$, $d = 0.04$; $|t|_{\text{Items}}(39) < -0.8$, $p = .43$, $d = 0.12$).

Thus, the priming effect of matching shapes and colors on the classification responses were multiplicative rather than additive. This pattern of effects contradicts the view that color information and shape information provide independent contribution to the representations that are activated when nouns referring to color-diagnostic objects are processed. In contrast, it is consistent with the idea that the verbal stimuli activated object representations that were based on an interactive integration of colors and shapes.

Response latencies and similarity ratings. Given that the perceived similarity of background pictures to actual fruits and vegetables follows a multiplicative similarity rule, the multiplicative integration view also predicts that a higher similarity of background picture to the referent of the stimulus word should be associated with faster classification responses. In order to investigate the effect of the similarity of background pictures to actual fruits and vegetables on response latencies in the classification task, we conducted multilevel analyses with random coefficients (Nezlek, 2001; Raudenbush & Bryk, 2002; Richter, 2006). A multilevel approach is required in this case because different participants received different combinations of background pictures and verbal stimuli. On the basis of multilevel models with random coefficients, it is possible to separate the total variance of response latencies into a proportion of variance between experimental items (level 1) and a proportion of variance between participants (level 2).

Moreover, it is possible to test whether and to what extent an effect of the similarity of background pictures to actual fruits and vegetables varies randomly between participants, i.e. the units of observation on level 2. We specified a random coefficient model with two predictors on level 1 and no predictors on level 2 (for the model equations and additional information, see Appendix D). Parameters were estimated with the Restricted Maximum Likelihood/Generalized Least Squares (RML/GLS) technique implemented in HLM 6 (Raudenbush, Bryk, Cheong, & Congdon, 2004). As predictors on level 1, we included the means and the standard deviations of the similarity ratings that were determined for each experimental item in Experiment 1. The means of the similarity ratings reflect the average perceived similarity across participants for particular combinations of background pictures and stimulus words, whereas the standard deviations reflect the degree of inconsistency of these ratings across participants. Both predictors were entered as uncentered variables. As criterion variable, we used the mean response latencies for correct responses after latencies deviating more than two standard deviations from the grand mean had been removed. In the specified model, the intercept, which reflects the estimated mean response latency across participants for background pictures with a mean similarity rating of 0, was estimated as 1015.5 (SE = 30.6, $t(73) = 33.2$, $p < .001$). The slope of the first predictor, the mean similarity ratings, was estimated as -44.0 (SE = 8.2) and it was significantly different from zero ($t(73) = -5.3$, $p < .001$). This indicates that the more similar to the fruit or vegetable denoted by the stimulus word the background picture was rated, the faster were the classification responses: A one-point difference in the mean similarity ratings was associated with a decrease in response latency of about 44 ms. The slope of the second predictor, the standard deviations of the similarity ratings, was estimated as 114.9 (SE = 31.3) and it was also significantly different from zero ($t(73) = 3.7$, $p < .001$). This indicates that the less consistent the similarity judgements of the participants in the norming study were for a given experimental item, the slower were the responses to this item in the classification task. We also tested the level-2 variance components that reflect the random fluctuation of intercept and slopes between participants. None of the variance components was significantly different from zero (intercept model: $\tau_0 = 13817$, χ^2 (73) = 85.0, $p = .16$; slope model for predictor 1: $\tau_1 = 112.4$, χ^2 (73) = 60.8, $p > .50$; slope model for predictor 2: $\tau_2 = 3214$, χ^2 (73) = 66.4, $p > .50$). These results indicate that the effects of the mean similarity ratings and their consistency were stable across participants.

To summarize, in line with the predictions derived from the multiplicative integration view and consistent with the experimental data, classification of fruits and vegetables names was facilitated to the extent that the background stimulus was similar to the actual fruit or vegetable denoted by the stimulus word. The inconsistency of similarity ratings between individuals, which is likely to be highly correlated with the uniformity in the appearances of a word's referent, was negatively associated with the ease of access to word meanings.

Given that access to word meanings was essential to provide the classification responses, the results of Experiment 2 corroborate the hypothesis that the comprehension of nouns which denote color-diagnostic objects involves the activation of object representations that combine color and shape in an interactive manner. However, it still remains a possibility that the multiplicative priming effects of color and shape were due to aspects of the particular task used in Experiment 2 rather than general characteristics of the underlying representations. For example, the classification of basic level category names with respect to superordinate level categories may have invoked specific strategies based on the retrieval of specific exemplars (cf. the instantiation principle, Heit & Barsalou, 1996). The following experiment was designed to rule out this possibility and demonstrate the generalizability of the findings to another task that requires access to word meanings.

Experiment 3

Experiment 3 was based on the same stimulus materials as Experiment 2 but used a lexical decision task. Lexical decisions require less attention to semantic processing than classification because orthographic information can be used to make these judgments. Nevertheless, semantic information plays a role in lexical decisions (Balota et al., 2004). Thus, lexical decision allows testing the alternative predictions of the additive combination view and the multiplicative integration view for a task that is associated with shallower semantic processing. As with the classification decisions in Experiment 2, the additive combination view predicts additive priming effects of color and shape on lexical decisions, whereas the multiplicative integration view predicts multiplicative priming effects, i.e. facilitation of lexical decisions only when both color and shape match. Again, given that the perceived similarities follow a multiplicative similarity rule, the multiplicative integration view makes the additional prediction that the lexical decision latencies should be negatively associated with the mean similarity rating for stimulus word and visual stimulus but positively associated with the interindividual inconsistency in the similarity ratings.

Method

Participants. Twenty-nine psychology undergraduates took part in Experiment 3. Of these, three were excluded from the analysis because they reported being myopic (self-rated severity of 5 or higher on a rating scale from 1 to 10) and not wearing corrective lenses. The remaining 26 participants (17 women and 9 men) had a mean age of 19.2 years (*SD* = 1.8).

Stimulus material. The experimental items (names of ten fruits and ten vegetables) and filler items (names of ten herbs and ten cereals) in Experiment 3 were identical to those used in Experiment 2. In addition, 40 phonologically and orthographically plausible nonwords (sampled from the ARC Nonword Database, Rastle, Harrington, & Coltheart, 2002) that matched experimental and filler words in length (number of letters) were included as stimuli. Twelve additional names of fruits, vegetables, herbs, and cereals (the same names as in Experiment 2) and twelve additional nonwords were used as practice items.

Procedure. The procedure of Experiment 3 closely followed the procedure used in Experiment 2. The main difference was that the participants in Experiment 3 performed a lexical decision task. Participants were told that words and meaningless strings of letters would appear one-by-one on the computer screen. They were instructed to indicate as quickly as possible by pressing one out of two response keys whether the stimulus appearing on the screen was a meaningful word or a meaningless string of letters. They operated the response keys with the index fingers of their left and their right hand. The assignment of response keys to words or nonwords was randomized across participants. The experiment started with a practice part where 12 words and 12 nonwords were presented. The actual experiment included 40 experimental trials, 40 filler trials, and 80 nonword trials in a randomized order, with each of the experimental items, filler items, and nonwords presented twice. The stimuli were presented in the same way as in Experiment 2, with the only difference that the onset of the background picture always preceded the onset of the presentation of the stimulus word or nonword by 200 ms. After the experimental trials, the same object recognition task as in Experiment 2 was given.

Design. The design was identical to the design of Experiment 2, with the exception that the SOA of background pictures and experimental stimulus words was held constant (given the lack of an effect for this factor in Experiment 2). Accordingly, the design was a 2 (color match vs. mismatch) X 2 (shape match vs. mismatch) design with repeated measurements on both variables. Again, there was an additional neutral condition that was used to determine the relative inhibition or facilitation of lexical decision responses. The assignment of experimental items to experimental conditions and the neutral condition was counterbalanced between participants. Filler items and background pictures as well as nonwords and background pictures were combined in a random manner, with the constraint that each background picture appeared equally often with experimental items and filler items. Likewise, each background picture appeared equally often with word and nonword stimuli.

Results and Discussion

The power of the hypothesis-relevant tests in the between-subjects analysis was .93 given the actual sample size and under the assumptions of a medium-sized effect (f = .25), a type-I error probability of .05 and substantial correlations (ρ = .75) between the levels of the within-subjects factors.

Lexical decision accuracy and object identification accuracy. Participants performed very accurately in the lexical decision task (proportion of correct responses: M = .99, SD = .08; see also Appendix B) as well as in the object recognition task (proportion of correctly identified fruits and vegetables: M = .95, SD = .05).

Response latencies. Response latencies for the experimental trials with correct responses were inspected for outliers. Latencies deviating more than two standard deviations from the condition mean (1.7% of all latencies) were eliminated. The grand mean of the adjusted response latencies was 604 ms (SD = 93). In an ANOVA performed on the adjusted response latencies, the main effect of color match vs. mismatch ($F_1(1,25) = 0.1$, $p = .76$; $F_2(1,19) = 0.1$, $p = .77$) was not significant. The main effect for shape match vs. mismatch was marginally significant in the by-subjects analysis ($F_1(1,25) = 3.9$, $p = .06$, $\eta^2 = .14$) and not significant in the by-items analysis ($F_2(1,19) = 2.9$, $p = .11$). However, there was a large ordinal interaction effect of the two independent variables that was significant in the by-subjects analysis ($F_1(1,25) = 6.2$, $p < .05$, $\eta^2 = .20$) and marginally significant in the by-items analysis ($F_2(1,19) = 4.3$, $p = .05$, $\eta^2 = .18$; Figure 2b). This interaction paralleled the interaction effect found in Experiment 2: When both color and shape information matched the typical color and shape of the fruit or vegetable denoted by the stimulus word, lexical decisions were 40 ms faster (SE_M = 15) than in the neutral condition ($t_{Subjects}(25) = -2.7$, $p < .05$, $d = 0.53$; $t_{Items}(19) = -2.4$, $p < .05$, $d = 0.53$). Matching color or matching shape alone, in contrast, did not lead to faster lexical decisions (for both comparisons: $|t|_{Subjects}(25) < 1.4$, $p > .18$, $d < 0.27$; $|t|_{Items}(19) < 0.9$, $p > .38$, $d < 0.21$). Moreover, there was no significant facilitation effect when both color and shape were mismatching ($|t|_{Subjects}(25) < 1.9$, $p > .07$, $d < 0.37$; $|t|_{Items}(19) < 1.5$, $p > .17$, $d < 0.31$). Thus, as in Experiment 2, the results of Experiment 3 corroborated the prediction derived from the multiplicative integration view that there is a multiplicative priming effect of color and shape information. No evidence was found, in contrast, for additive priming effects that would support the additive combination view.

Response latencies and similarity ratings. The predictions of the multiplicative integration view concerning facilitation effects of the similarity of background pictures to actual fruits and vegetables were tested on the basis of the same random coefficient model that was applied to the data from Experiment 2 (Appendix D). The intercept reflecting the estimated mean response latency (in ms) across participants for background pictures with a mean similarity rating of 0 was estimated as 597.3 ($SE = 26.6$, $t(25) = 23.6$, $p < .001$). The slope of the mean similarity ratings was estimated as -20.5 ($SE = 3.9$) and it was significantly different from zero ($t(25) = -5.3$, $p < .001$). As in Experiment 2, the higher the rated similarity for a given experimental item, the faster were the lexical decisions: A one-point difference in the mean similarity rating was associated with an average decrease in response latency of 20.5 ms. The slope of the second predictor, the standard deviations of the similarity ratings, was estimated as 53.7 (SE = 15.3) and it was significantly different from zero ($t(25) = 3.5$, $p < .01$). Again parallel to the results from Experiment 2, the less consistent participants' similarity judgements in the norming study were for a given item, the slower were the responses to this item in the lexical decision task. With the exception of the variance component of the intercept model (intercept: $\tau_0 = 6837.6$, χ^2 (25) =

38.6, $p < .05$), none of the level-2 variance components slopes were significant (slope mode for predictor 1: $\tau_1 = 3.8$, χ^2 (25) = 10.9, $p > .50$; slope model for predictor 2: $\tau_2 = 137.3$, χ^2 (25) = 13.1, $p > .50$), indicating that the effects of the mean similarity ratings and their consistency were stable across participants. In line with the multiplicative integration view, access to word meanings was facilitated to the extent that the background stimuli were similar to the words' referents. On the other hand, access to word meanings was slowed down the higher the interindividual inconsistency of similarity ratings was. One possible explanation is that this predictor is likely to be related to diversity in the appearances of the referents of the fruits and vegetables names.

In sum, the results for the lexical decision latencies closely replicated the results that were obtained for the classification latencies in Experiment 2. Thus, the predictions of the multiplicative integration view were supported with a task that directly addresses lexical access.

Experiment 4

In Experiment 4, we used the same stimuli as in the previous experiments in a word naming task to investigate whether nouns denoting color-diagnostic objects activate object representations based on an interactive integration of colors and shapes even when access to word meanings is not the focus of the task. In word naming tasks, participants read out words that are not embedded in a phrase or sentence context. Conceptually, this task requires little or no attention to semantic processing because proficient readers should be able to translate the graphemic representation of familiar words more or less directly into a phonemic representation. Still, semantic variables influence the ease of word naming (Balota et al., 2004), indicating that access to word meaning is involved in word naming to a moderate extent. As a consequence, we expected the same albeit weaker priming effects as in Experiments 2 and 3. Again, the multiplicative integration view predicts a multiplicative priming effect of color and shape, as opposed to an additive effect that is implied by the additive combination view. Moreover, the multiplicative integration view predicts a facilitation effect on word naming that depends on the similarity of the visual stimulus to the fruit or vegetable denoted by the stimulus word. In addition to an analysis of the data from Experiment 4, we conducted a joint analysis of the experimental data from Experiment 2 to 4 in order to obtain quantitative information about the generalizability of the effects observed in all three experiments.

Method

Participants. Forty-eight psychology undergraduates took part in Experiment 4. Of these, six were excluded from the analysis because they reported being myopic (self-rated severity of 5 or higher on a rating scale from 1 to 10) and not wearing corrective lenses. The remaining 42 participants (26 women and 16 men) had a mean age of 19.0 years (SD = 1.2).

Stimulus materials. The experimental items (names of ten fruits and ten vegetables) and filler items (names of ten herbs and ten cereals) in Experiment 4 were identical to those used in Experiment 2. Twelve additional names of fruits, vegetables, herbs, and cereals (the same names as in Experiment 2) were used as practice items.

Procedure. The procedure of Experiment 4 closely followed the procedures used in Experiments 2 and 3. The main difference was that the participants in Experiment 4 performed a word naming task. They were instructed that words would appear one-by-one on the computer screen and that their task would be to read aloud these words quickly and accurately. Participants wore headsets with a built-in microphone that was connected to a PST Serial Response Box. We recorded the word naming latencies from the onset of the presentation of the stimulus word to the triggering of the voice key by the participant's response. The stimulus word remained on the screen for 500 ms after the voice key had been triggered. Throughout the experiment, the experimenter was in the same room as the participant in order to register inaccurate responses (e.g., wrong pronunciations) or erroneous triggering of the voice key (e.g., by coughing). The experiment started with 24 practice trials. The actual experiment included 40 experimental trials and 40 filler trials, with each of the experimental and filler items presented twice. The stimuli were presented in the same way as in the previous experiments. As in Experiment 3, the onset of the background picture always preceded the onset of the presentation of the stimulus word by 200 ms. After the experimental trials, the same object recognition task as in Experiments 1 and 2 was given.

Design. As in Experiment 3, the design was a 2 (color match vs. mismatch) X 2 (shape match vs. mismatch) design with repeated measurements on both variables. Again, there was an additional neutral condition that was used to determine the relative inhibition or facilitation of word naming latencies, and the assignment of experimental items to experimental conditions and the neutral condition was counterbalanced between participants. Filler items and background pictures were combined in a random manner, with the constraint that each background picture appeared equally often with experimental items and filler items.

Results and Discussion

The sample size in Experiment 4 was chosen to ensure that the power of the hypothesis-relevant tests was sufficient to detect small to medium effects ($f = .15$). The power to detect effects in this range ($f = .15$) was .77 under the assumptions of a type-I error probability of .05 and substantial correlations ($\rho = .75$) between the levels of the within-subjects factors.

Word naming accuracy and object identification accuracy. The proportion of faulty trials in the word naming tasks was low (proportion of valid experimental trials: $M = .99$, $SD = .01$; see also Appendix B). The accuracy in the object recognition task was high (proportion of correctly identified fruits and vegetables: $M = .95$, $SD = .06$).

Naming latencies. Naming latencies for the valid experimental trials were inspected for outliers. Latencies deviating more than two standard deviations from the condition mean (3.0% of all latencies) were eliminated. The grand mean of the adjusted naming latencies was 623 ms (*SD* = 70). An ANOVA performed on the adjusted naming latencies revealed neither a main effect of color match vs. mismatch ($F_1(1,41) = 0.8$, $p = .78$; $F_2(1,19) = 0.2$, $p = .89$) nor a main effect for shape match vs. mismatch ($F_1(1,41) = 3.6$, $p = .07$; $F_2(1,19) = 2.2$, $p = .16$). However, there was a medium-sized interaction effect of the two variables that was significant in the by-subjects analysis ($F_1(1,41) = 4.8$, $p < .05$, $\eta^2 = .11$) but failed to reach significance in the by-items analysis ($F_2(1,19) = 1.7$, $p = .22$; Figure 2c). For the comparisons with the neutral condition, the same pattern emerged in both the by-subjects and the by-items analysis. Similar to the results of Experiments 1 and 2, naming latencies were 12 ms shorter ($SE_M = 5$) than in the neutral condition when both color as well as shape information matched the typical color and shape of the fruit or vegetable denoted by the stimulus word ($t_{Subjects}(41) = -2.2$, $p < .05$, $d = 0.33$; $t_{Items}(19) = -2.1$, $p = .05$, $d = 0.46$). Matching color or matching shape alone, in contrast, did not lead to faster naming latencies (for both comparisons: $|t|_{Subjects}(41) < 0.8$, $p > .46$, $d < 0.14$; $|t|_{Items}(19) < 0.7$, $p > .53$, $d < 0.06$). Also, there was no facilitation effect when both color and shape were mismatching ($|t|_{Subjects}(41) < 0.5$, $p > .68$, $d < 0.07$; $|t|_{Items}(19) < 0.7$, $p > .50$, $d < 0.16$). In sum, a multiplicative priming effect predicted by the multiplicative integration view was also found for word naming, a task that requires little attention to semantic processing of the verbal stimuli.

Naming latencies and similarity ratings. The effects of the similarity of background pictures to actual fruits and vegetables on the word naming latencies was investigated on the basis of a random coefficient model structured in the same way as the model that was applied to the data from Experiments 2 and 3 (Appendix D). The intercept reflecting the estimated mean naming latency (in ms) across participants for background pictures with a mean similarity rating of 0 was estimated as 586.6 ($SE = 16.4$, $t(41) = 35.9$, $p < .001$). The slope of the mean similarity ratings was estimated as -11.0 (*SE* = 3.4) and it was significantly different from zero ($t(41) = -3.1$, $p < .01$). The more similar the visual stimulus in an experimental item was to the actual fruit or vegetable denoted by the stimulus word, the faster the names of fruits and vegetables were named: A one-point difference in the mean similarity rating was associated with a decrease in naming latency of 11 ms. The slope of the standard deviations of the similarity ratings was estimated as 73.2 (*SE* = 11.4) and it was significantly different from zero ($t(41) = 6.4$, $p < .001$). Again parallel to the results from the previous experiments, the less consistent participants' similarity judgements in the norming study were for a given item, the slower the fruit or vegetable name in this item was named. Except for the variance component for the intercept model ($\tau_0 = 5449.7$, $\chi^2\,(41) = 69.6$, $p < .01$) none of the level-2 variance components was significant ($\tau_1 = 27.4$, $\chi^2\,(41) = 30.3$, $p > .50$; $\tau_2 = 170.9$, $\chi^2\,(41) = 27.4$, $p > .50$), indicating that these effects were stable across participants. In line with the multiplicative integration view, the ease with which written words can be named depended on the similarity of a concurrently presented visual stimulus to exemplars of the words' referents. The interindividual inconsistency of the similarity ratings, which is likely to be directly related to diversity in the appearances of a word's referent, slowed down word naming latencies. As with the experimental results, the average effects were smaller than in the previous experiments, reflecting the shallower depth of semantic processing in the word naming task.

Joint analysis of Experiments 2 to 4. We conducted a joint ANOVA of the data from Experiments 2 to 4 with the experimental task as between-subjects variable. In this analysis, the adjusted response latencies were used in order to be able to investigate differences in the mean response times between the experimental tasks. The interaction of color match vs. mismatch and shape match vs. mismatch predicted by the multiplicative integration view was significant in the by-subjects analysis ($F_1(1,139) = 5.7$, $p < .05$, $\eta^2 = .04$) and marginally significant in the by-items analysis ($F_2(1,77) = 3.8$, $p = .06$, $\eta^2 = .05$). As in the separate analysis for the three experiments and as predicted by the multiplicative integration view, responses were faster than in the other three conditions when both color and shape information matched ($M = 725$ ms, $SE_M = 13$; for all comparisons: $|t|_{Subjects}(141) > 2.8$, $p < .01$, $d > .24$; $|t|_{Items}(79) > 2.7$, $p < .01$, $d > .30$). However, neither color match ($M = 760$ ms, $SE_M = 15$) nor shape match alone ($M = 763$, $SE_M = 15$) yielded faster responses compared to the condition in which both color and shape mismatched ($M = 750$ ms, $SE_M = 14$). Thus, the joint analysis of the data from Experiments 2 to 4 yielded the same pattern of a multiplicative priming effect that was found in the separate analyses and that is predicted by the multiplicative integration view. Even with the greater statistical power achieved by the joint analyses, the priming effect of color or shape alone, as it was predicted by the additive combination view, did not emerge. In addition, we found a strong main effect of experimental task ($F_1(2,139) = 201.9$, $p < .001$, $\eta^2 = .74$; $F_2(2,77) = 183.8$, $p < .001$, $\eta^2 = .83$). Overall, response latencies were slower in the classification task ($M = 1026$ ms, $SE_M = 14$) compared to both the lexical decision task ($M = 600$ ms, $SE_M = 24$) and the word naming task ($M = 623$ ms, $SE_M = 19$). This result is consistent with the assumption that classification necessitated greater attention to semantic processing than the other two tasks. We also computed *z*-score transformed condition means for each participant (cp. Faust, Balota, Spieler, & Ferraro, 1999, p. 788) so that we were able to compare the magnitude of the facilitation effects across experiments. After *z*-score transformation, the difference of the double-match condition to the neutral condition was greater in the two tasks that involve semantic processing, classification ($M_{diff} = -0.55$, $SE_M = 0.20$) and lexical decision ($M_{diff} = -0.78$, $SE_M = 0.28$), compared to the naming task which is likely to involve very little semantic processing ($M_{diff} = -0.39$, $SE_M = 0.19$). However, the three-way interaction of experimental task, color match vs. mismatch, and shape match vs. mismatch was not significant ($F_1(2,139) = 0.76$, $p = .47$; $F_2(2,77) = 0.46$, $p = .64$).

General Discussion

The goal of this article was to compare two alternative accounts of how different types of perceptual information are integrated in word access. According to the additive combination view, object representations activated during word access are based on an additive (linear) combination of different types of perceptual information. The multiplicative integration view, in contrast, assumes that words activate object representations that are based on a multiplicative (interactive) integration of perceptual features. In four experiments, we tested competing predictions of these two accounts on how matching color and matching shape facilitate the processing of nouns that denote color-diagnostic objects. In Experiment 1, we established that in line with the multiplicative integration view, participants combined color and shape multiplicatively when judging the similarity of a schematic picture to the referents of names of fruits and vegetables (comparable to multiplicative similarity rules implemented in interactive cue models of categorization, e.g., Medin & Schaffer, 1978). Experiments 2, 3, and 4 used a broad range of word processing tasks, from a task that required deep semantic processing (classification) over a task that required lexical access (lexical decision) to a task that involved only shallow semantic processing (word naming). Despite the diversity of tasks, the results from the three experiments exhibited a highly consistent pattern: We found multiplicative priming effects of color and shape but no indication for additive priming effects of the two types of perceptual information. In particular, only if both color and shape of the visual stimulus matched the typical appearance of referents of the verbal stimulus, word processing was facilitated. These findings corroborate the idea that the object representations activated in word access are based on an interactive combination of perceptual features rather than an additive combination of independent features.

The interpretation in terms of an interactive combination of color and shape is further supported by supplemental correlational analyses performed on the data of Experiments 2 to 4. In all three experiments, the similarity of the visual stimulus to actual referents of the verbal stimulus had a positive effect on the magnitude of the priming effects. In addition, the more consistent the similarity of a visual stimulus to actual referents of the verbal stimulus had been rated in a norming study, the larger the priming effect was. Given that the perceived similarity of the visual stimuli to actual fruits and vegetables followed a multiplicative similarity rule, these findings are in line with the multiplicative integration view. Apparently, the similarity of a visual stimulus to actual referent objects and the homogeneity in the appearance of these objects enhanced responses in the word processing tasks.

The remarkable consistency of the experimental and correlational results across Experiments 2 to 4 notwithstanding, there was also one difference between experiments that is worth noting. Both the average multiplicative priming effect of color and shape and the average similarity effects were larger in the classification and in the lexical decision task compared to the word naming task. Thus, the average magnitude of facilitation effects tended to covary with the amount of attention to semantic processing necessitated by the task, implying that the interactive activation of perceptual features is linked to access to word meanings.

Implications for Experiential Theories of Language Comprehension

What are the implications of these results for experiential theories of language comprehension? Generally speaking, they suggest that it might be worthwhile to take a closer look at the nature of perceptual representations involved in language comprehension. So far, most of the research following an experiential approach has focused on substantiating the general claim that perceptual representations are activated during comprehension (Zwaan, 2004). At this point, it seems promising to move on to a perspective that goes beyond the activation of single perceptual dimensions such as color, shape, or orientation. Experiments similar to those reported here, in which several perceptual dimensions are investigated simultaneously, are likely to be informative with respect to the structure of perceptual representations and the processes that operate on these representations. In particular, the present experiments demonstrate for a specific type of linguistic stimuli, i.e. nouns that denote color-diagnostic objects, that perceptual features are combined in a non-linear (multiplicative) rather than a linear (additive) manner during language processing.

For the present experiments, we chose color and shape as the perceptual dimensions of interest because these dimensions are involved in recognizing color-diagnostic objects. Accordingly, the experiential view of language comprehension predicts that both types of perceptual information should be part of the perceptual simulation that people perform when understanding words with color diagnostic referents. Is it likely that these results can be generalized to perceptual dimensions other than shape and color? In principle, representations of referent objects activated during language comprehension can include all kinds of perceptual dimensions (not only in the visual modality), as long as these dimensions are characteristic of objects that a linguistic expression refers to. Given that shape is the universal cue in visual object recognition, shape information will almost certainly be part of these representations. Other perceptual dimensions are used in the recognition of some objects, making it likely that these dimensions will also be included in the representations activated when words that denote these objects are processed. Besides color, orientation and size are likely candidates that are probably relevant in a larger number of cases. For example, studies in object recognition have shown that the ease of recognizing asymmetrically shaped objects with a canonical orientation is negatively related to the amount of spatial transformations that is necessary to establish a canonical orientation (e.g., Jolicoeur, 1985; Tarr & Bülthoff, 1998). Against this background, it seems reasonable to assume that words denoting objects with a canonical orientation (e.g., *tree*, *car*, *house*) activate perceptual representations that include shape as well as orientation. Similar arguments might hold for size that is a prominent perceptual characteristic of many objects. However, due to the fact that the size of objects is more strongly view-point dependent than shape and orientation, size might be relevant particularly when words are presented within a linguistic context that provides a spatial frame of reference by specifying view point, perspective, and distance (Zwaan, 2004).

Although the findings reported in this article are compatible with a number of representational models, they cohere more strongly with some theories of the structure of conceptual representations than with others. First of all, that a non-linear combination of features forms the basis of conceptual representations is endorsed by interactive cue models of categorization that have been applied with considerable success to category learning experiments (e.g., Nosofsky, 1992) as well as to natural language categories (Storms, 2004). The idea of a non-linear combination of category features can be combined with exemplar models (e.g., Kruschke, 1992; Medin & Schaffer, 1978; Minda & Smith, 2002; Nosofsky, 1984, 1986, 1992) as well as with models based on summary representations such as prototypes (e.g.,Minda & Smith, 2002; Nosofsky, 1992). The data reported here do not speak to the issue of whether perceptual representations should be conceptualized as exemplars or summary representations. From the perspective of the experiential view of language comprehension, it seems plausible to assume that both types of representations are important for language comprehension, albeit in different roles. On the one hand, the idea that conceptual representations are composed of exemplars is very close to the assumption that the meaning of linguistic expressions is based on perceptions and sensory experiences of comprehenders that have coincided with experiencing these expressions themselves. For this reason, exemplar models have a great deal to offer as parsimonious representational accounts that fit well with experiential theories of language comprehension. On the other hand, some topics such as the problem of conceptual combination and the comprehension of novel expressions present particular challenges that might limit the explanatory scope of the exemplar view (but see Prinz, 2002). In these cases, summary representations such as schemata and prototypes might come into play. Barsalou's (1999) theory of perceptual symbol systems demonstrates how representations of this kind can be understood in terms of an experiential approach to cognition.

Convergence Zones and the Anterior Temporal Lobes as the Neural Bases of Integrating Perceptual Information

A second group of theories that are related to the multiplicative integration view, but is neurally based, originates from Damasio's convergence zone theory (Damasio, 1989; Damasio & Damasio, 1994; see also Barsalou, Simmons, Barbey, & Wilson, 2003). According to this theory, conceptual representations are based on re-enactments of patterns of neuronal activation in sensory-motor areas of the brain. The activation patterns of feature neurons that are involved in perceiving shape, color, or orientation of an object, for example, are stored by neuronal assemblies called *convergence zones*. Convergence zones are distributed in higher-order association cortices, limbic cortices, and subcortical nuclei such as the basal ganglia and amygdala (Damasio, Tranel, Grabowski, Adolphs, & Damasio, 2004). The exact location of convergence zones of particular concepts is a matter of probability and can vary between individuals. However, functional imaging and lesion studies have identified distinct large-scale regions that correspond to broad categories of concrete objects. For example, lesion data reported by Damasio et al. (2004) have shown that the recognition of familiar faces depends most likely on regions in the right temporal lobe, angular gyrus, and lateral occipital cortices. In contrast, the recognition of tools depends on regions in the left mesiotemporal lobe. When a conceptual representation of an object from the respective category is activated, for example by recognizing the object or comprehending a word that refers to it, conjunctive neurons located in these convergence regions activate the feature neurons in the sensory cortices, thereby reproducing a pattern of activation that resembles the pattern that originally emerged during perception. Convergence zones can bind different types of visual information, information from several modalities, and sensory and motor information. A related but more radical view on the role of sensory-motor information for the representation of concepts in the brain has been put forward by Gallese and Lakoff (2005). These authors argue that conceptual representations in the brain are *multimodal* in the sense that they are based on functional clusters involving premotor and parietal neurons that respond to more than one modality. The best known examples of such neurons are mirror neurons that respond to both seeing and performing specific actions (e.g., Gallese, Fadiga, Fogassi, & Rizzolatti, 1996). A third approach that shares many assumptions with convergence zone theory and the notion of multimodality is the *distributed-plus-hub view* suggested by Patterson, Nestor, and Rogers (2007). The central claim of this view is that despite being based on a network of distributed modality-specific regions of the brain, neural representations of semantic knowledge require some kind of convergent architecture with a central hub that associates different kinds of sensory, motor, and linguistic information. The neurons and synapses in this hub, which is assumed to be located in the anterior temporal lobes, support the interactive activation of representations based on several modalities and multiple types of perceptual information. Strong neuropsychological evidence for this view is provided by studies of patients with semantic dementia that typically exhibit degeneration of the anterior temporal lobes. Computational evidence comes from a connectionist model by Rogers and McClelland (2004; see also McClelland & Rogers, 2003). By way of representational units that bind together object features based on different types of perceptual information, such a model can simulate various aspects of semantic processing such as generalization and restructuring of conceptual knowledge.

Importantly, conjunctive neurons in convergence regions (as assumed by Damasio et al., 2004), in functional clusters (as assumed by Gallese & Lakoff, 2005) or in a semantic hub located in the anterior temporal lobes (as assumed by Patterson et al., 2007) store concepts by representing *patterns* of sensory-motor information. When conceptual knowledge is activated by comprehending a word, conjunctive neurons storing these patterns of sensory-motor information are activated. These assumptions closely map onto the assumptions of the multiplicative integration view.

How might an approach such as convergence zone theory or the distributed-plus-hub view account for our findings? First consider the case of a double match (shape match plus color match). In this case, the co-presence of features of the prime results in the simultaneous activation of specific feature neurons, which results in strong bottom-up activation of specific conjunctive neurons that are also active when the entity is perceived. When the word is presented, these same conjunctive neurons receive activation, which, in turn activate the feature neurons coding for shape and color to create a mental simulation of the entity. On this account, the pathway is activated from the bottom up by the prime, thus facilitating the mental simulation prompted by the word, which in turn facilitates categorization, lexical-decision, and naming responses. Next, consider what happens when only a single match is present. In this case, specific shape and color feature neurons are activated, but the relevant conjunctive neurons receive little activation (in cases where the shape-color combination matches some other visual experience, irrelevant conjunctive neurons may be activated). Likewise, when a mismatch occurs on both dimensions, the relevant conjunctive neurons receive little activation, and thus the relevant neuronal pathways are not primed for the mental simulation. Thus, according to this account, strong activation of the conjunctive neurons, which code for the co-occurrence of the perception of particular color-shape combinations, is crucial for priming to occur.

Limitations and Directions for Future Research

One limitation of the paradigm used in Experiments 2 to 4 is that the visual stimuli are rather schematic. For example, a tomato is neither exactly round nor focal red. A related problem is that different colors form a psychological space with continuous similarity relations. Thus, in future experiments it would be more appropriate to consider different colors as more or less similar to the typical color of a word's referent rather than to consider them as matching or mismatching. Furthermore, participants may differ in the nature or extent of their visual experiences with particular target objects. Ideally, one would want to reduce this source of variance. That is, one would want to have visual stimuli that provide much closer matches to the participants' experiences and one would want to be able to control the participants' visual experiences with particular stimuli. In a new series of experiments, we are trying to accomplish these objectives by having participants learn novel visual stimuli with novel names and specific combinations of features. This paradigm will allow us to examine more closely how combinations of visual object features influence language processing. The robust pattern of the current data makes us optimistic about this endeavor.

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Appendix A: Color and Shape Norms for Names of Fruits and Vegetables Used as Verbal Stimuli in Experiments 1 to 3

Stimulus	Color (Percent of Mention)[a]	Color Typicality[a] *M* (*SD*)	Shape Rating[b] *M* (*SD*)
apple	red (100)	5.63 (0.65)	-3.07 (0.88)
asparagus	green (96)	5.74 (0.69)	3.79 (0.58)
banana	yellow (100)	5.46 (1.14)	2.93 (2.05)
carrot	orange (100)	5.63 (0.88)	3.27 (1.10)
cherry	red (96)	5.58 (0.78)	-3.67 (0.49)
corn	yellow (100)	5.42 (1.06)	3.13 (1.19)
cucumber	green (96)	5.83 (0.39)	3.64 (0.63)
grape	purple (83)	5.67 (0.76)	-3.07 (1.28)
jalapeno	green (92)	5.71 (0.55)	1.67 (1.59)
lemon	yellow (100)	5.58 (1.02)	-1.60 (1.55)
lettuce	green (100)	5.92 (0.28)	-3.07 (1.03)
lime	green (96)	5.96 (0.20)	-1.93 (1.22)
pea	green (96)	5.75 (0.61)	-4.00 (0.00)
plum	purple (92)	5.39 (0.78)	-3.33 (0.82)
pumpkin	orange (100)	5.63 (0.71)	-3.20 (0.56)
radish	red (75)	5.37 (0.83)	-3.08 (0.67)
strawberry	red (100)	5.58 (1.02)	-1.67 (1.35)
tangerine	orange (100)	5.58 (0.78)	-3.87 (0.35)
tomato	red (100)	5.63 (0.77)	-3.53 (0.52)
zucchini	green (83)	5.45 (1.06)	3.57 (1.09)

Note. Percent of Mention: Percentage of participants who mentioned this color as a typical color, Color Typicality: Range from 1 to 6; Shape Rating: Range from -4=round to 4= elongated. [a] $n = 24$, [b] $n = 15$.

Appendix B: Accuracy Data (Experiments 2, 3, and 4)

Table 1 (Appendix B). Mean proportion of correct responses (with standard errors) in the experimental conditions of Experiments 2, 3, and 4.

	Color	
Shape	Match	Mismatch
Experiment 2 [a]		
Match	.90 (.01)	.91 (.01)
Mismatch	.92 (.01)	.92 (.01)
Experiment 2 [b]		
Match	1.00 (.00)	1.00 (.00)
Mismatch	1.00 (.00)	0.99 (0.01)
Experiment 3 [c]		
Match	.99 (.01)	.98 (.01)
Mismatch	.99 (.00)	.99 (.01)

Note. Standard errors of the means computed across subjects. [a] $n = 74$, [b] $n = 26$, [c] $n = 42$.

Appendix C: Response Latencies in Milliseconds (Means and Standard Errors) in the Experimental Conditions of Experiments 2, 3, and 4

Experiment 2: Classification

	Color		
	Match	Mismatch	Total
Shape			
Match	984 (20)	1067 (23)	1026 (19)
Mismatch	1030 (22)	1037 (21)	1033 (18)
Total	1007 (18)	1052 (19)	

Experiment 3: Lexical Decision

	Color		
	Match	Mismatch	Total
Shape			
Match	580 (17)	601 (17)	591 (17)
Mismatch	624 (29)	591 (16)	608 (21)
Total	602 (22)	596 (16)	

Experiment 4: Word Naming

	Color		
	Match	Mismatch	Total
Shape			
Match	614 (11)	624 (12)	619 (11)
Mismatch	631 (10)	623 (11)	627 (10)
Total	622 (10)	623 (11)	

Note. Mean response latencies (with standard errors) in the neutral condition were 1041 ms (21) in Experiment 2, 620 ms (20) in Experiment 3, and 625 ms (12) in Experiment 4.

Appendix D: Model Equations for Multilevel Models (Experiments 2, 3, and 4)

The multilevel models for analyzing the effects of the perceived similarity of the visual stimuli and actual fruits and vegetables on the response latencies in Experiments 2, 3, and 4 were two-level random coefficient models with no predictors on level 2 (random coefficients regression model, Raudenbush & Bryk, 2002). This type of multilevel models is similar to a traditional (fixed coefficients) regression model, with the only difference that the intercept and slopes are regarded as varying randomly between level-2 units. The supplemental analyses performed on the data of Experiment 2, 3, and 4 require a random coefficients regression model in order to account for the facts that the response latencies are provided by different participants, and that these participants received different combinations of visual and verbal stimuli. Thus, the response time data have a multilevel structure with experimental items as level-1 units nested within participants as level-2 units. Ignoring this nested structure and the dependencies that it creates within the data would bear the risk of severely biased estimates of the parameters and their standard errors. As a consequence, hypothesis tests based on these estimates might be misleading.

The random coefficients regression model used in Experiments 2,3, and 4 has two parts, the level-1 model with experimental items as units of observation and the level-2 models with participants as units of observation. The elements of the level-1 model can be interpreted in a way that is analogous to an ordinary regression model:

$$Y_{ij} = \beta_{0j} + \beta_{1j} X_{1\,ij} + \beta_{2j} X_{2ij} + r_{ij}\,. \quad \text{(Level 1, experimental items)} \qquad (1)$$

In this model, the responses latencies Y_{ij} provided by participant j for experimental item i are regressed on the mean similarity ratings X_{1ij} and the standard deviation of the similarity ratings X_{2ij} for the experimental items. The parameters β_{1j} and β_{2j} reflect the slopes of the two predictors. Parameter β_{0j} reflects the intercept, i.e. the estimated response latency when both predictors take on the value zero. The final element, r_{ij}, is a level-1 error term that reflects the deviations of the actual from the predicted values.

Despite the similarity of the level-1 model to an ordinary regression model, there is one small but important difference: The parameters β_{0j}, $\beta_{1j,}$ and β_{2j} carry the index j, meaning that the parameter estimates are allowed to vary between participants. In the level-2 equations 2a, 2b, and 2c, this variability is modeled as a function of a level-2 intercept $\gamma_{.0}$, which represents the mean estimate across all participants, and a level-2 error term $u_{.j}$, which captures the deviations of each participant's parameter estimates from the mean parameter estimate:

$\beta_{0j} = \gamma_{00} + u_{0j}$. (Level 2, participants, intercept model) (2a)

$\beta_{1ij} = \gamma_{10} + u_{1j}$. (Level 2, participants, model for the slope of X_1) (2b)

$\beta_{2ij} = \gamma_{20} + u_{2j}$. (Level 2, participants, model for the slope of X_2) (2c)

The presence of the error terms $u_{.j}$ in the level-2 models is unique to random coefficient models. Unlike traditional fixed coefficient regression models, the error variance is split up in variance components that are located on level 1 (experimental items, variance σ of the error term r_{ij}) and level 2 (participants, variance $\tau_{.}$ of the error terms $u_{.j}$). In this way, the nested structure of the response latencies is accounted for. Moreover, it is possible to derive conclusions about the stability of parameter estimates across participants by estimating the variances $\tau_{.}$ of the level-2 error terms $u_{.j}$ and testing whether these variances are significantly different from zero.

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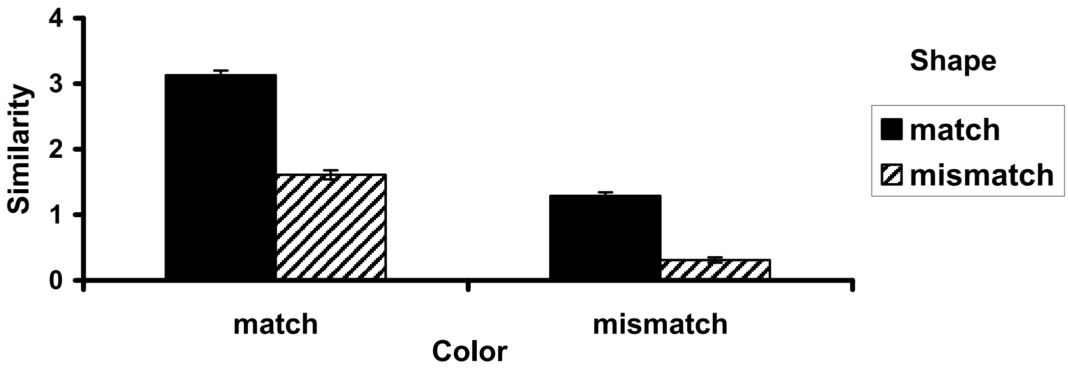
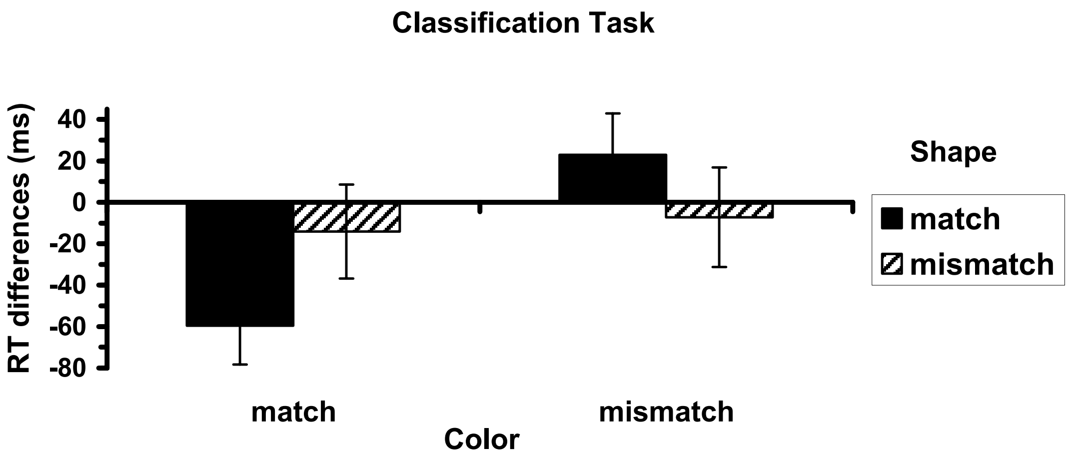
Figure Caption

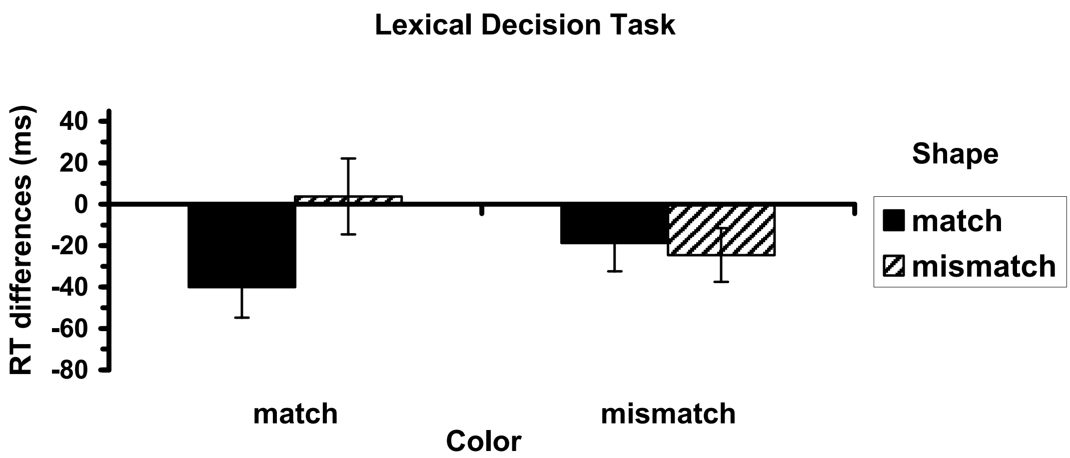
Figure 1. Effects of matching and mismatching color and shape information on ratings of the similarity of schematic visual stimuli to actual fruits and vegetables in Experiment 1 (rating scale from 0=*not similar at all* to 4=*very similar*). Error bars represent the standard error of the mean.

Figure 2. Effects of matching and mismatching color and shape information on (a) classification latencies (Experiment 2), (b) lexical decision latencies (Experiment 3), and (c) word naming latencies (Experiment 4). Responses latencies are displayed as differences to the neutral condition. Error bars represent the standard error of the mean.

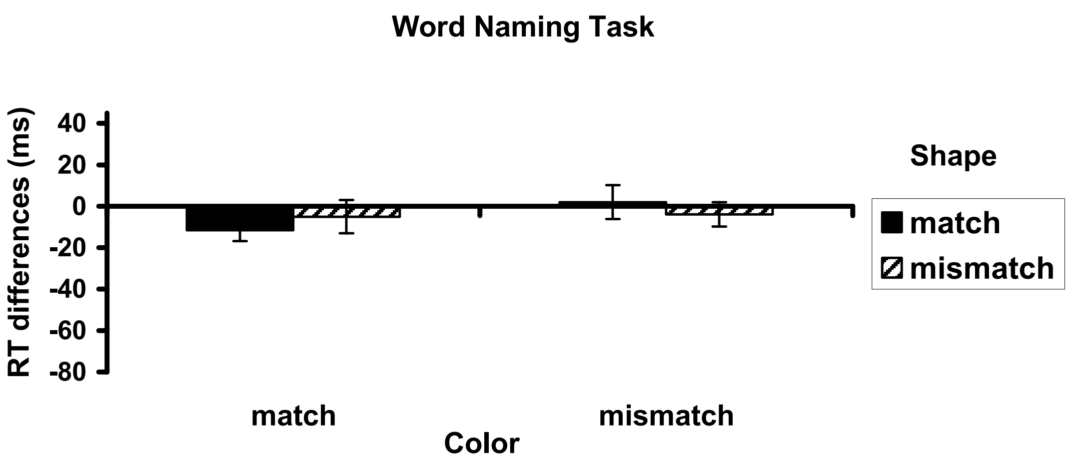

4
3
2
1
0
Similarity
Shape
match
mismatch
match
mismatch
Color


Classification Task
RT differences (ms)
40
20
0
-20
-40
-60
-80
match
mismatch
Color
Shape
match
mismatch

a)


Lexical Decision Task
RT differences (ms)
40
20
0
-20
-40
-60
-80
match
mismatch
Color
Shape
match
mismatch

b)


Word Naming Task
RT differences (ms)
40
20
0
-20
-40
-60
-80
match
mismatch
Color
Shape
match
mismatch

c)