DISCRIMINABILITY MATTERS:

ON MEMORY FOR FORM AND COLOUR

by

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ABSTRACT

The hypothesis that discriminability differences between forms and colours resulted in subsequent memory differences was evaluated in a series of four experiments. A perceptual identification paradigm was used in which participants made speeded same/different responses to sequentially presented form and colour pairs (Experiments 1 and 2). Once discriminability was equated across the form and colour dimensions, these forms and colours were combined to create unified percepts (e.g., a red cone). These combined features were tested to ensure that the equality of discriminability persisted when form and colour were combined (Experiment 3). These combined stimuli were then used to assess *memory* for form and colour when separate features varied (Different Form, Different Colour) and when both features varied (Colour x Form) in Experiment 4. Evidence supported better memory for form than colour for separate features but no difference in memory for form and colour was found when features were combined.

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Discriminability Matters: On Memory for Form and Colour

Objects can vary in several ways (e.g., size, texture, form, colour); these object properties are referred to as feature dimensions. Each dimension has a set of values (e.g., large, shiny, spherical, blue) associated with it that we use in order to describe the objects we experience. Thus, feature values can be thought of as the adjectives that allow us to describe, remember and differentiate objects. The goal of the present research was to explore whether some features are discriminated and remembered better than others.

Discriminability is the capacity to discern differences among items. Posner and Mitchell (1967) posited that our ability to accurately detect whether items are the same or different might provide the infrastructure for all higher-level information processing. Object feature dimensions provide cues for differentiating among objects: People must identify disparities, among one or more dimensions, to discriminate among objects. Research has shown that the more distinct an item is from its surroundings, the easier it is to discriminate. Nickerson (1967) found that the time to discriminate between objects varies inversely as a function of the number of feature dimensions (e.g., size, colour, shape) that differ. For example, participants were faster to indicate that a large blue square was different from a small red circle (three different features) than a small blue square (one different feature). Thus, objects with more overlapping features are discriminated more slowly than objects with fewer overlapping features.

Similar findings have been found using visual search tasks where participants must locate a target in amongst a set of distractors. For example, Neisser (1964) found that the time to detect a target letter varied as a function of the extent of feature overlap between the target letter and the distractor letters. Hence, the target (Z) was more difficult to detect in an array of distractors with straight lines (F, T, X, N) than in an array of curvilinear distractors (e.g., P, C, Q, D). Similarly, Townsend (1971) found that the probability of confusing pairs of letters varied as a function of the feature overlap between the letters. For example, a Q has only one feature that differentiates it from an O, thus Qs and Os are highly confusable. In contrast, Xs and Os do not share any features and are therefore much less likely to be confused. Typically, it takes participants longer to detect a target as the number of distractors increases, however, Treisman and Gelade (1980) found that some targets “pop-out” from distractors and these targets are detected quickly regardless of the number of distractors. For example, detecting the letter R amongst P’s and Q’s is more difficult, as indexed by requiring more time to detect, as the number of P’s and Q’s increases, because people need to serially scan to detect differences. However, the letter O “pops-out” amongst W’s and V’s, so regardless of the number of distractors, the O is detected quickly. Thus, discriminability is adversely affected by the extent of feature overlap in the objects to be discriminated.

Given the evidence that discriminability differences in letters affect performance in visual search tasks and identification (e.g., Neisser, 1964; Townsend, 1971; Treisman & Gelade, 1980), it is plausible that these differences would carry forward to affect object recognition and memory. Hence, the reported differences in form and colour in the object recognition and memory literature (e.g., Biederman & Ju, 1988; Brown, Wade, & Herdman, 2007; Wheeler & Treisman) may be attributable to perceptual-level discriminability differences within their respective stimuli and to differences in the representational strengths of these features in memory. Therefore, the first goal of this thesis is to isolate a series of feature values from two feature dimensions (i.e., colour and form) that are perceptually equally discriminable. Once this first goal has been achieved, these feature values will be used in a memory paradigm to explore whether one feature dimension is more likely to be remembered than the other.

Memory for Objects in Space

Objects that people encounter every day can serve as landmarks and reference points that provide descriptions of relationships in space and thus help people create cognitive maps of environments. A cognitive map is a term coined by Tolman (1948) in order to describe how rats appeared to rely on an internal representation of their environment and inferred that humans also rely on cognitive maps. The feature values of objects used as landmarks are tied to locations in cognitive maps (e.g., the red brick school-house).

Although the storage capacity of visual short-term memory is assumed to be limited to only three or four items (Luck & Vogel, 1997), the constructivist view proposes that a cognitive map accrues over repeated exposures (Tversky, 1993). For example, on the first exposure to a new environment, perhaps only a few items are partially processed, but with each subsequent encounter, more objects (with more detail) are incorporated into our mental representation. Tversky used the term cognitive collage to describe the disparate bits of information acquired from an environment (e.g., objects and their locations) that can be augmented over time and experience to create an increasingly detailed representation. These representations can be subsequently integrated into a comprehensive cognitive map. Rensink's (2000) theory explains our ability to successfully navigate in a familiar environment by relying on information from a cognitive map when the external environment is not available for visual sampling (e.g., in the dark). Successful navigation in the absence of visual information requires accurate cognitive maps depicting objects, their constituent features, and their relative location in space.

Object Memory and Recognition

In addition to using objects as landmarks, objects can also be stored in memory without being tied to a location in space. Indeed, much of the classic work on object recognition memory (e.g., Biederman, 1987) relies on paradigms that are location independent. In these cases objects are remembered based on their appearance, purpose and meaning. It is an important ability to store object information in memory when they are not tied to a specific location because it allows us to compare the features of current objects to previously experienced objects and their mental representations in order to recognize them as familiar or novel objects regardless of the environment in which the objects are contained. This extrapolation allows for conservation of cognitive resources. Researchers often rely on participants' performance for individual features (e.g., colour and form) in order to make inferences about how objects are stored in memory when there is no contextual information.

Memory for Form and Colour

Memory for form and colour appears to be inconsistent among experiments and tasks. It has been shown that form provides the basis for object recognition (e.g., Biederman, 1987). However, form and colour have been found to interact such that colour information contributes to object recognition when form is ambiguous or degraded (Tanaka & Presnell, 1999). In contrast to the object recognition literature, there is evidence from attention literature that colour changes are more accurately detected than form changes (e.g., Allen et al., 2006; Wheeler & Treisman, 2002). However, these studies have investigated memory for object features independent of location.

There is evidence that an object's form is remembered better than its colour when features are tied to specific locations, (Brown, et al., 2007). Clearly, there are discrepancies pertaining to whether object recognition / memory is primarily driven by form or colour features. Whether or not an object is tied to a given location (e.g., whether an object is being used to create a cognitive map) may provide some explanation for this discrepancy. However, it is also possible that, these discrepant results are due to the physical properties of the selected stimuli. Specifically, the values from one feature dimension may have been systematically more physically discriminable from each other than the values from the other dimension. In order to understand how perceptual-level differences between colour and form discriminability could manifest themselves in recognition / memory tasks, it is important to review how object features are encoded.

Feature Binding

Many researchers concur that forming enduring internal representations of new objects and environments critically depends on cognitive processes including working memory and attention (e.g., Allen et al., 2006; Rensink, 2000; Wheeler & Treisman, 2002). Objects must first be attended to before they can be stored as representations in memory. Object features (e.g., form, colour, orientation) are processed in different regions of the visual cortex independently and in parallel (Livingstone & Hubel, 1987) and then combined to form a single percept. This process of combining sets of features is known as binding (see Treisman, 1999; Wheeler & Treisman, 2002).

Treisman and Gelade (1980) found that the process of binding separate features into a unified whole and to a location in space is driven by focused visual attention. Once object features are bound, this object maintains its identity despite the passage of time and location changes (Kahneman, Treisman, & Gibbs, 1992). Wheeler and Treisman (2002) posited that these bound representations conserve short-term memory capacity through a process called chunking (Miller, 1956) whereby smaller pieces of information are combined into a larger 'chunk.' Miller (1956) posited that maintaining a 'chunk' in memory requires the same amount of mental capacity as that required by a single smaller piece of information. With respect to the current issue, feature values from different feature dimensions (e.g., yellow, cube) of the same object can be remembered with no measurable performance cost, whereas two values from the same dimension (e.g., yellow, purple) compete for storage (Wheeler & Treisman, 2002). This intra-dimensional competition for storage occurs regardless of whether the features belong to a single object or multiple objects.

Furthermore, attention is not only required to initially bind an object's features, but also to maintain this bound representation in memory. It has been repeatedly shown that without persistent focused visual attention, an object's constituent features become unbound (e.g., Horowitz & Wolfe, 1998; Wolfe, 1999). Similarly, tasks that require additional cognitive resources result in preserved memory for independent features but impair memory for the bound representations of these features. For example, when participants concurrently performed mental arithmetic (Stefurak & Boynton, 1986) and encoded simple shape and colour bindings, memory for individual features was unaffected, but memory for how the features were bound was impaired. Specifically, participants were better at recognizing whether they had seen a shape *or* colour had been in a previous array than how the shapes *and* colours were paired as whole objects (Stefurak & Boynton, 1986). Thus, these added cognitive demands appear to interfere with the maintenance of links between features. Furthermore, Allen et al. (2006) showed that links between features are prone to disintegrate due to interference from subsequent objects and as a function of the initial presentation order. Participants were more accurate at discerning whether a colour and shape combination had been in a test array if the test array objects were presented simultaneously rather than sequentially. Further, participants were less accurate at discerning if a colour and shape combination had been in a sequentially presented array the closer it was to the beginning of the sequence. Thus, focal attention is required both to initially create and maintain bound representations of objects.

Once people have created enduring representations of object's features, whether bound or independently stored, usually through repeated exposure, practice or rehearsal, objects are recognized as being familiar (i.e., have been previously encountered) or novel. However, novel objects can often be classified as belonging to a category of familiar objects based on similarities between the novel object and the object representation. The dominant view is that object recognition is primarily based on form (rather than colour) information. In his recognition-by-components (RBC) theory, Biederman's (1987) states that objects are recognized based on the simple volumetric primitives (geons) of which they are comprised. For example, a barbell is comprised of two disks attached by a central cylinder. Object identity is then determined by matching the volumes and the composition of a current percept with a previously acquired representation acting as a template. Thus perceivers can identify both familiar and novel objects based on the visual overlap with the established memory representation. This claim is supported by evidence showing that objects can be easily identified when presented as black and white images, line drawings, and even images that are partially occluded (Biederman, 1987). Biederman (1987) posited that other dimensions, such as colour, supplement our mental representations but do not facilitate object recognition.

As Biederman (1987) posited, although colour may supplement the recognition process, form information is a more reliable cue for object identification. This is especially true given that mass production allows most objects can to be made in a multitude of colours, thus rendering colour non-diagnostic. As a result, viewers may place more emphasis on remembering form information, as it is more likely to result in accurate object recognition than colour.

Many natural objects are strongly associated with a specific color (e.g., bananas with yellow). In cases such as these, colour is said to be diagnostic of an object's identity. Therefore, if colour contributes to object memory, then its contribution would most likely be found under diagnostic conditions. Consistent with this view, the contribution of colour in both object (e.g., Tanaka & Presnell, 1999) and scene (e.g., Oliva & Shyns, 2000) recognition critically depends on whether the stimuli have diagnostic colors associated with them.

According to Tanaka et al.'s (2001) "Shape + Surface" model of object recognition (see Figure 1), shape (i.e., form) information (depicted as the larger input module) primarily activates an object's representation, but colour and potentially texture can contribute to disambiguating objects when they are occluded, distorted or otherwise degraded. Tanaka et al. (2001) concurred with Biederman (1987) that recognition is primarily driven by form information, but argued that there are conditions where colour and (potentially) texture contribute to object recognition. Colour often provides the basis for differentiation between two objects that are in terms of their form identical (e.g., a blue pen and a red pen). Tanaka et al. (2001) asserted that colour and form information interact such that colour facilitates recognition when objects have similar forms (e.g., birds), but not objects have dissimilar forms (e.g., tools). Colour may also play an important role in primate vision when an object's form is partially occluded such as when foraging for ripe fruit amongst foliage (e.g., Mollon & Jordan, 1988; Regan et al., 2001). Thus, according to Tanaka et al.'s (2001) model, form is the dominant cue for object recognition, but other surface cues such as colour are important for recognition when form information is non-diagnostic or has been somehow degraded (e.g., occluded).

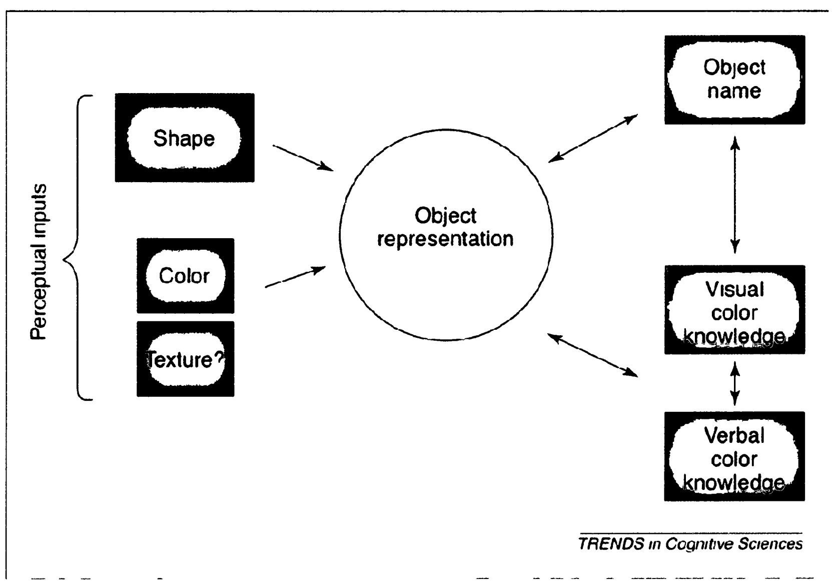

Figure 1. Tanaka et al.'s (2001): "Shape + Surface" Model of Object Recognition

An important distinction made by Tanaka et al. (2001), is that perceptual inputs (i.e., shape, colour and texture) provide bottom-up information to activate object representations, whereas an object's name and visual and verbal colour knowledge activate an object's representation in a top-down manner. Tanaka et al. relied on neuropsychological evidence to support the modularity of "visual colour knowledge" and "verbal colour knowledge" but evidence from recognition studies also supports this claim (e.g., Naor-Raz, Tarr & Kersten, 2003; Ostergaard & Davidoff, 1985). Specifically, the mode of activation of an object's representation (image-based vs. lexical) appears to influence whether or not colour contributes to object recognition in verification, naming and categorization tasks.

Object verification tasks require participants to confirm or deny whether a word is congruent with a subsequently presented image. Thus, the word in a verification task activates a lexical representation, which then activates its corresponding visual representation that is compared to an image. Biederman and Ju (1988) reported that diagnostically coloured photographs and line drawings were verified equally quickly. Thus, because diagnostic color information did not facilitate object verification, they inferred that surface information (e.g., color, texture) provides only secondary cues to an objects' identity. Biederman and his colleagues did not claim colour is not encoded, or that it is encoded more slowly than form; rather they argued that the colour information was not recruited for object recognition. Similarly, Ostergaard and Davidoff (1985) reported that normally and abnormally (e.g., yellow banana vs. purple banana) coloured colour-diagnostic objects were verified equally well. Thus, Ostergaard and Davidoff (1985) argued that if colour had provided additional information during recognition, then it should have taken longer to verify the abnormally coloured images because they are incongruent with our experience. Given that Biederman and Ju (1988) and Ostergaard and Davidoff (1985) did not find any facilitation or interference effects of diagnostic colour in object verification, they concluded that colour is not involved in recognition. However, this conclusion was based on the results from verification tasks, with the premise that lexical representations successfully activate visual (image-based) knowledge.

Although diagnostic colour does not appear to influence object recognition on verification tasks, it does appear to affect object naming and categorization. Ostergaard and Davidoff (1985) reported that colour-diagnostic fruits and vegetables were *named* faster if they were presented in colour than in black and white. Furthermore, Price and Humphreys (1989) reported faster categorization times when stimuli were presented in normal than in abnormal colours. Naor-Raz et al. (2003) concluded that diagnostic colour is an intrinsic property of an object's pictorial (image-based) representation, because they found Stroop-like interference effects for abnormally colored objects. However, no Stroop-like interference effects were reported when the objects were represented lexically or semantically. These findings suggest that an object's colour information is recruited for recognition purposes, but only when the object's representation is activated by an image.

Feature Discriminability

In most of the aforementioned studies on the relative contribution of form and colour information to object recognition, the relative discriminability of the features in the stimulus sets was not considered. This seems to be a critical oversight, given that the relative contributions of form and colour information to object recognition might hinge on the specific feature values of the stimuli. Tanaka and Presnell (1999) selected objects that were equated based on shape diagnosticity (i.e., the extent to which objects can be identified strictly on shape information). When equated for shape diagnosticity, colour was recruited for object recognition in a verification task, which contradicts previous findings (i.e., Biederman & Ju, 1988; Ostergaard & Davidoff, 1985). Although Tanaka and Presnell equated the discriminability of features within a dimension (i.e., form), no object recognition or object memory studies have been found that have attempted to empirically equate inter-dimensional stimulus discriminability between dimensions (e.g., colour and form).

Researchers typically choose their stimuli subjectively and assume that they are equally discriminable across different feature dimensions. For example, Wheeler and Treisman's (2002) stimuli were "selected from the set of red, yellow, green, blue, violet, white, brown, and black, chosen to maximize discriminability" (p. 51). Thus, any memory / recognition / change detection differences between feature dimensions (e.g., between colour and form) may occur if the values within one feature dimension are more or less discriminable than those from another dimension. Thus, ascribing any differences in the recruitment of feature information to higher-order cognitive processes may not be valid because the unequal discriminability of the features in the selected stimulus set may have precluded one dimension (e.g., colour) from being as strongly represented in memory as the other dimension (e.g., form) due to the varying featural / visual overlap. Clearly, the amount of featural overlap between to objects will affect how easily they can be confused and, therefore, identified (e.g., Neisser, 1964; Treisman & Gelade, 1980). Thus, if the feature values from one dimension are more similar than those in the other dimension, then additional resources (e.g., increased attention) may be required to process the features from one dimension, resulting in impaired acquisition and / or more rapid decay of this feature dimension compared to another feature dimension.

If one accepts the importance of equating feature discriminability between dimensions in assessing the relative contributions of these dimensions (e.g., colour and form), then the evidence that form plays a more important role than colour in object recognition (e.g., Biederman, 1987; Biederman & Ju, 1988) and object memory (Brown, Herdman, & Wade, 2007; Mitroi, 2008; Monkman, Brown, & Herdman, 2007) may be an artifact of the physical properties of the set of the stimulus sets used in these experiments. Conversely, evidence that colour plays a more important role than form (e.g., Wheeler & Treisman, 2002) may also be due to discriminability differences inherent to the stimuli.

Memory for Object Form and Colour

Brown et al. (2007) and Monkman et al., (2007) found that an object's form is more memorable than its colour when attempting to remember where an object was located, even though colour and form were equally descriptive of the object's identity. In these studies, participants explored (real and virtual) rooms populated with simple objects created by crossing forms (i.e., cube, cone, sphere) with colours (i.e., blue, red, yellow, green). Each object was unique in terms of its form and colour combination. After each exposure to the room, participants attempted to recall the locations of the objects in terms of their colour and form. In Brown et al., participants were more likely to make colour errors than form errors when recalling the location of objects in both real and virtual environments. Monkman et al. also reported that participants made more colour errors than form errors in both free and forced recall paradigms, indicating that Brown et al.'s results were not due to a response methodology that allowed participants to separate their colour and form responses. Mitroi (2008) used the same paradigm, but partitioned objects into subsets of three or four objects (by physically separating them such that only a few were visible at a time). Under these viewing conditions, the memory advantage for form information reported by Brown et al. and by Monkman et al. was eliminated. Mitroi found that structural segmentation facilitated the binding of object features, which eliminated the discrepancies between colour and form representations in memory. In sum, an object's form was more memorable than its colour in both real and virtual environments (Brown et al.), using both free and forced recall (Monkman et al.). However, when viewers are exposed to only a few objects at a time, there are no differences in memory for an object's form and colour (Mitroi).

The objective of the present thesis is to determine whether an object's form is remembered better than its colour once perceptual discriminability between these feature dimensions has been equated. Experiments 1, 2 and 3 were devoted to establishing the equal perceptual discriminability of the form and colour stimuli. Experiment 4 assessed memory for form and colour. In addition to investigating object memory when form and colour are *combined*, Experiment 4 also compared performance across two conditions where colour and form were separated: In one condition, form varied and colour did not, whereas in the other condition, colour varied and form did not.

Overview of the Present Research

In order to isolate a set of form and colour stimuli that were equally discriminable between dimensions, speeded same / different (two alternative forced choice) perceptual identification task was used. It was assumed that pairs of colours or pairs of forms with more featural / visual overlap would require more time to discriminate and / or be more error prone. In Experiment 1, participants compared pairs from a set of 16 forms and 16 colours to assess discriminabilty within the colour and form dimensions. Certain pairings were difficult to discriminate (high error rates) and some pairings could not be discriminated at all (i.e., chance performance) under these timing parameters. The pairings that yielded low discriminability performance were eliminated and the remaining stimuli were further reduced based on the reaction times and error rates associated with discriminating the pairings in an attempt to make the colours and forms equally perceptually discriminable. Nine forms and nine colours remained. This reduced set was retested using the same paradigm in Experiment 2. The results from Experiment 2 indicated that these nine forms and nine colours were equally discriminable at a perceptual level. That is, the average reaction time and error rate for discriminating the forms was statistically equal to the average reaction time and error rate for discriminating the colours. These nine forms and nine colours were equally discriminable at a perceptual level. In Experiment 3, the forms and colours were combined to form a single percept (e.g., a blue cube). These percepts were then displayed in the perceptual discriminability paradigm to determine whether or not these colours and forms were still equally discriminable when they were combined. There were no significant differences in reaction times and only slight differences between the error rates for detecting colour and form differences in Experiment 3. These nine forms and colours were therefore considered to be perceptually equally discriminable whether separated (Experiment 2) or combined (Experiment 3).

These nine colours and nine forms were used to explore the relative contribution of form and colour information to object memory in Experiment 4. Given that these colours and forms were perceptually equally discriminable, any differences in the relative contribution of colour and form could then be ascribed to how object features are represented and stored in memory and not to perceptual-level effects. Experiment 4 assessed memory for objects in three conditions. In two conditions, one feature dimension was held constant while the other dimension varied. Specifically, in the Different Colour condition, objects had one form but differed in colour. Similarly, in the Different Form condition, objects had one colour but differed in form. Thus, when the objects only differed along one feature dimension (i.e., Different Colour, Different Form) only one type of error can be made. In these two conditions only one type of error can be made. That is, only colour errors can be made in the Different Colour condition and only form errors in the Different Form condition. In the third condition, both feature dimensions were manipulated to create unique colour / form combinations. Experiment 4 assessed the frequencies of form and colour errors when only one feature varies (i.e., Different Colour, Different Form) and the types of errors (colour vs. form errors) when both features vary (i.e., Colour x Form).

In the combined features condition (i.e., Colour x Form) participants could make form errors (i.e., correct colour, incorrect form) and colour errors (i.e., correct form, incorrect colour). The types of errors were used to infer how these objects are represented in memory. If an object is represented as a bound entity, then the whole object (i.e., both its form and colour) should decay from memory, which should produce equal form and colour errors. Alternatively, if an object's features are not bound and if they have unequal representational strength in memory or if they are susceptible to differential decay, then there should be unequal colour and form error rates.

Experiment 1

The objective of Experiment 1 was to determine whether a spectrum of 16 forms and colours, were perceptually equally discriminable.

Method

Participants

Twenty Carleton undergraduate (12 males and 8 females) volunteers participated in a one-hour study for course credit. All participants in this and all subsequent experiments reported normal colour vision and normal or corrected-to-normal visual acuity.

Materials

Visual stimuli for this and all subsequent experiments were displayed on a gray background using E-prime version 1.1.4.4 on a LG Studioworks E700B, 17-inch flat screen CRT monitor running at a resolution of 800 x 600. The display was slaved to a computer powered by an Intel Xeon 3.06 GHz processor, running Windows XP and using an ATI Radeon 9800 Pro video card. Participants responded using a standard computer keyboard. Participants pressed the “1” key using their left hand for a same response and pressed the “0” using their right hand to make a different response.

Stimuli

Stimuli and masks were centered on the screen and subtended a visual angle of approximately 5.84 degrees, both vertically and horizontally. Sixteen colours were selected from the “pure” Pantone® colour swatches provided by Adobe Photoshop version 10.0.1 (see Appendix A), that spanned the colour spectrum. Given that there was no available “spectrum” of forms to create a subset of form primitives, 16 of Biederman’s (1987) geons were selected (see Appendix A). The forms were modeled in Google

Sketch-up 6 and some were truncated and / or slightly modified to subjectively match (a priori) the discriminability of the colour stimuli. The forms were modeled in white with gray shading and were shown from an isometric perspective on a white background (as shown in Appendix A). Images were adjusted using Adobe Photoshop version 10.0.1 such that the forms subtended the largest possible visual angle within the limits of the visual angle of the colour patches.

Design

Two feature blocks (form and colour) consisted of 16 practice trials and 480 experimental trials for a total of 32 practice trials and 960 experimental trials. There were an equal number of same / different trials in the practice and experimental conditions. Feature blocks were counterbalanced across participants such that the colour block was first for half of the participants and the form block was first for the other half. Within each feature block, each form (or colour) was paired with the remaining 15 forms (or colours) to create the "different" trial stimulus pairings. Each stimulus was also paired with itself 15 times to create the same trial pairs. Thus each form (or colour) appeared as the first stimulus in a pairing, 30 times (15 different and 15 same trials). Practice trials were created by randomly selecting parings from the full set such that there were an equal number of same / different trials and every stimulus was displayed at least once.

Procedure

For every trial in this and all subsequent perceptual identification experiments, the sequence of stimuli displayed was as follows: A small, black fixation cross, subtending a visual angle of approximately 2.29 degrees, was presented centrally for 1000 ms. The first form / colour was then displayed for 100 ms immediately followed by a pattern mask (i.e., an array of "&" signs) for 200 ms. A blank screen was then displayed for 800 ms, followed by second stimulus (ISI = 1000 ms) which was displayed for 100 ms and then masked for 200 ms (during which participants could respond). Finally, a blank screen was displayed until response, or until 5000 ms had elapsed. The trial sequence is depicted in Figure 2. Reaction times and accuracy were recorded. Participants were instructed to respond as quickly and as accurately as possible. No feedback was given with respect to performance. Instructions were shown on screen and read aloud by the experimenter. The experimenter observed the initial practice trials to ensure comprehension. Four breaks (of participant-determined duration) were provided at equal intervals within a block. Task instructions were reiterated on screen following each break.

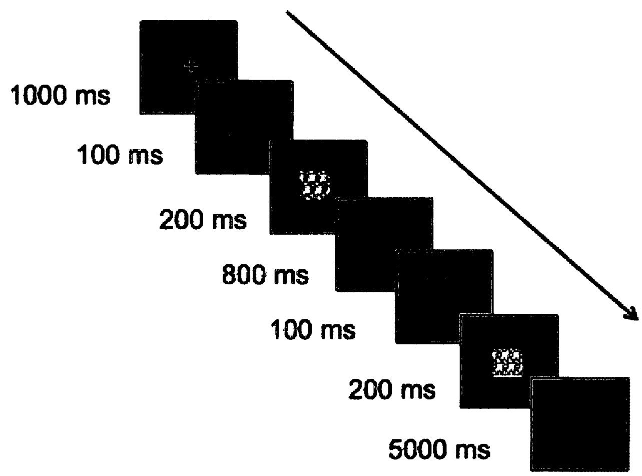

Figure 2. Example of a trial sequence.

Results

Reaction Times

Reaction times for accurate trials were subjected to a recursive outlier procedure (Van Selst & Jolicoeur, 1994) that eliminated trials that were three or more standard deviations above or below the mean reaction time for that condition. This resulted in an elimination of 2.94% of the accurate RT data. The remaining data were subjected to a 2 (Feature: Form vs. Colour) x 2 (Decision: Same vs. Different) repeated measures ANOVA. There was no main effect of Feature ($F < 1$). However, there was a main effect of Decision, $F(1, 19) = 20.78$, $MSE = 1896.98$, $p < .001$, $\eta_p^2 = .52$. Specifically, participants responded more quickly in the Same condition ($M = 581$ ms, $SE = 24.82$) than in the Different condition ($M = 626$ ms, $SE = 24.90$). Furthermore, there was a significant Feature by Decision interaction, $F(1, 19) = 5.58$, $MSE = 414.30$, $p < .05$, $\eta_p^2 = .23$. Specifically, the differences between Same and Different decision latencies were greater for forms than for colours.

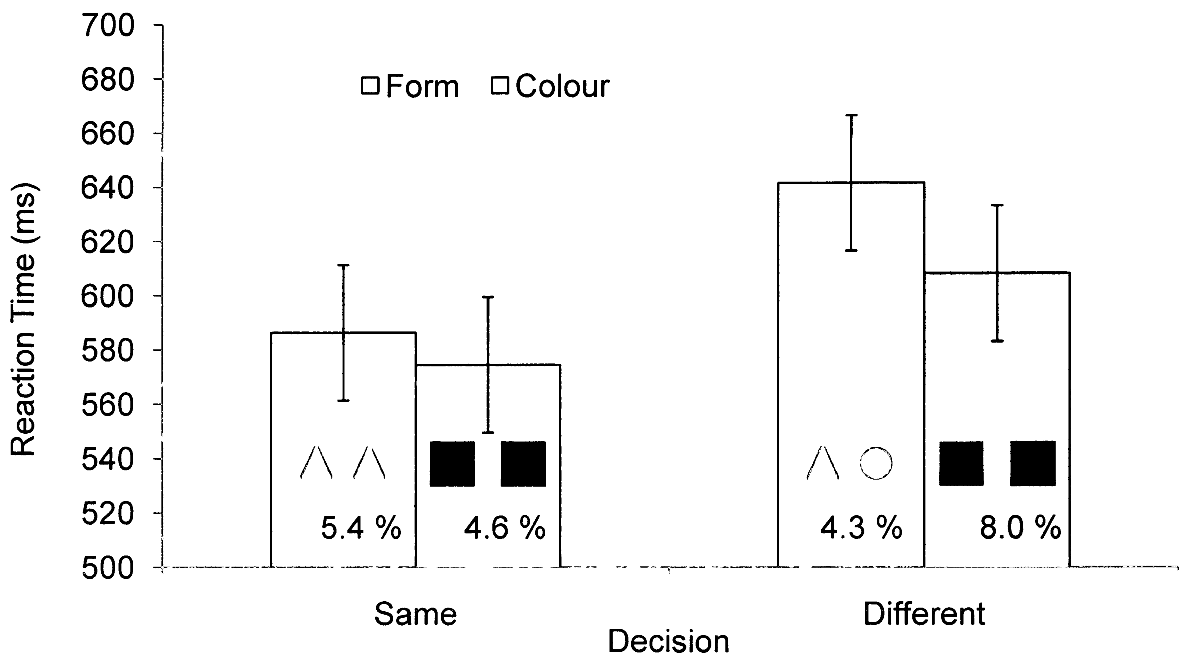

Figure 3. E1. Reaction times and error rates as a function of Decision and Feature with standard error bars and examples of each condition.

Errors

No participant's mean error rate was beyond +/- 3 standard deviations from mean error rate for each condition, thus all participants' data were included in the analysis. Participants made fewer errors for Forms (M = 4.8 %, SE = .8 %) than for Colours (M = 6.3 %, SE = .6 %), as there was a significant main effect of Feature, F (1,19) = 9.86, MSE < .001, p < .01, η_p^2 = .34. Errors did not vary by Decision however, F (1,19) = 1.95, p > .05. Furthermore, there was a significant Feature by Decision cross-over interaction, F (1,19) = 35.94, MSE < .001, p < .001, η_p^2 = .65. Participants made fewer errors in the Different condition than in the Same condition for forms (i.e., 4.3 % vs. 5.4 %), but more errors in the Different condition than in the Same condition for colours (i.e., 8.0 % vs. 4.6%). A Bonferroni adjustment to control for multiple comparisons showed that only the difference between the error rates for colours were significantly different from each other, $p < .001$.

Discussion

Although there was no evidence of any discriminability differences between these 16 forms and 16 colours in the RT data, the error data show that it was significantly more difficult to discriminate between the colours than between the forms. Given that participants made fewer form errors than colour errors (collapsed across same and different trials), it can be inferred that it was more difficult to discriminate between the colour pairings than the form pairings. Additionally, the RT data provided support for the Fast Same Effect (FSE). That is, same trials were responded to significantly faster than different trials. Nickerson (1972) reported in the literature that observers are faster to report that two objects that are the same than if they are different (i.e., the FSE). As Nickerson argued, this effect is surprising because, for a person to determine that two (or more) objects or patterns are different, only one discrepancy needs to be detected. Whereas, a same judgment requires that all features must be compared to ensure a complete match, which would require more time. However, although same responses are faster, they tend to be more error prone than different responses, thus producing a speed accuracy trade-off (Krueger, 1978). However, contrary to Krueger's (1978) findings, error rates for same and different responses in Experiment 1 were approximately equal, thus there was no evidence of a speed accuracy trade-off.

In order to explore why colours were more error prone and therefore less discriminable than forms, an item analysis of the error rates for each form and colour pairing was completed. This revealed that the same / different decisions for one colour pairings were worse than chance (57.4 % incorrect). Participants commonly indicated that some colour pairings were the same, when they were, in fact, different. Some of the form pairs were also nearly indiscriminable (46.2 % incorrect). The magnitude of difficulty participants had discriminating particular pairings prompted a reduction in both the form and colour stimuli.

Intuitively, it would seem appropriate to eliminate these two colour pairs and reanalyze the data. However, this would lead to unequal cell sizes and may not be a valid approach given that discriminability is likely to be critically dependent on the other items within the stimulus set. That is, even though the data from these two pairs could be eliminated, this would not eliminate the influence from these stimuli on the other trials in the experiment. Therefore, the following criteria were adopted to reduce size of the stimulus set for the next experiment. Specifically, one of stimulus from a colour / form pair that had an average error rate of more than 20% and / or an average reaction time exceeding 800 ms was removed. These criteria were adopted in order to eliminate an equal number of form and colour stimuli. Nine forms and nine colours remained (see Appendix A for stimuli that were rejected). This reduced stimulus set was used in Experiment 2.

Experiment 2

The objective of Experiment 2 was to determine if the nine forms and nine colours selected from the previous experiment were equally discriminable in terms of both reaction times and error rates.

Method

Participants

Twenty Carleton undergraduate students (7 males and 13 females) participated for course credit. One participant was removed from all subsequent analyses because his/her error rate was 3 standard deviations above the mean error rate.

Stimuli

The 18 stimuli were selected based on the criteria described in the discussion section for Experiment 1 and are shown in Appendix B.

Design

The design, apparatus and procedure were identical to Experiment 1A with the following exceptions. Two feature blocks (form and colour) consisted of 18 practice trials and 432 experimental trials for a total of 36 practice trials and 864 experimental trials. Within each feature block, each form / colour stimuli was paired with the remaining 8 forms / colours to create the "different" trial pairings and presented three times each. Each stimulus was also paired with itself to form the "same" trial pairs. Thus each stimulus in each feature block appeared as the first stimulus, 48 times (24 different and 24 same trials).

Procedure

The procedure was identical to Experiment 1.

Results

Reaction Times

Reaction times for accurate trials were subjected to the same recursive outlier procedure described in Experiment 1. This resulted in an elimination of 2.71% of the RT data. The remaining data were subjected to a 2 (Feature: Form vs. Colour) x 2 (Decision: Same vs. Different) repeated measures ANOVA. There was no main effect of Feature ($F < 1$). However, participants responded significantly faster in the Same condition (M = 614 ms, SE = 30.04) than in the Different condition (M = 654 ms, SE = 31.10), $F(1, 18) = 20.89$, $MSE = 1478.67$, $p < .001$, $\eta_p^2 = .54$. Specifically, There was no evidence to suggest for a Feature by Decision interaction, ($F < 1$). The data are shown in Figure 4.

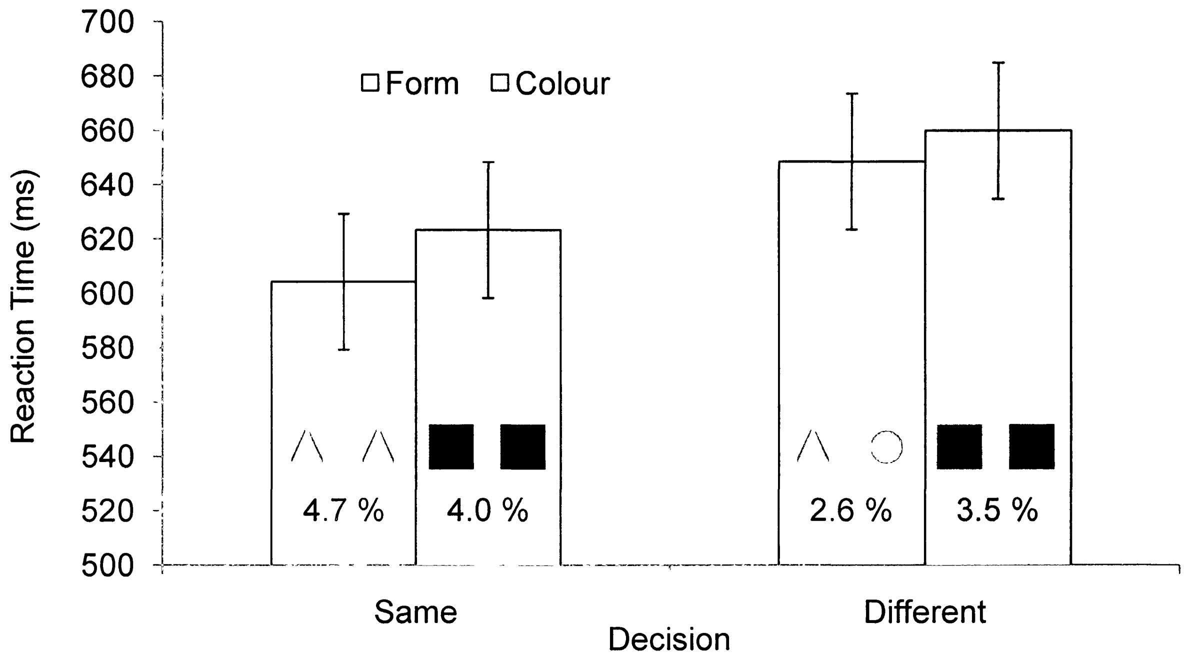

Figure 4. E2. Reaction times and error rates as a function of Decision and Feature with standard error bars and examples of each condition.

Errors

There was no main effect Feature, ($F < 1$). However, the main effect of Decision approached significance $F(1,18) = 3.61$, $MSE = .001$, $p = .07$, $\eta_p^2 = .17$. Specifically, there were fewer errors in the Different condition (M = 3.0 %, SE = 0.4 %) than the Same condition (M = 4.3%, SE = 0.8 %). Additionally, the Feature by Decision interaction also approached significance $F(1,18) = 3.35$, $MSE < .001$, $p = .08$, $\eta_p^2 = .16$. It appears that the effect of Decision (Same vs. Different) affects the forms more than the colours. Specifically, the difference in accuracy between Same and Different conditions was 2.1 % for Forms (with lower accuracy in the Same condition) but only 0.5 % for Colours (see Figure 4).

Discussion

There was no evidence in either the RT or error data that the nine colours were any harder to discriminate from each other than the nine forms. The RT data yielded a FSE, with faster responses on same trials than on different trials. However, in contrast to Experiment 1, but consistent with the literature (e.g., Krueger, 1978) there was evidence for a speed accuracy trade-off, with marginally higher error rates ($p < .10$) in the Same condition than in the Different condition. The finding of no difference in the RT and error data between the colour and form trials is evidence that these nine colours and nine forms are, equally discriminable within dimensions. However, this experiment only presented these features separately. This effect may not generalize when colours are combined with forms to create a unitary percept. The purpose of Experiment 3 is to examine whether there are any discriminability differences between these forms and colours when they are shown as combined features (e.g., a blue cube). In the Different condition, either the form or the colour (not both) will be different, whereas in the Same condition, both the form and the colour will be identical. In order to explore this hypothesis, the forms and colours from Experiment 2 were crossed to create 81 unique objects.

Experiment 3

The objective of Experiment 3 was to determine if the nine forms and nine colours that were deemed equally discriminable within dimensions in Experiment 2 remained equally discriminable when tested as combined features.

Method

Participants

Twenty-four Carleton undergraduate students participated for course credit (8 males and 16 females).

Stimuli

Eighty-one unique objects were created by crossing the nine forms and nine colours used in Experiment 2 (see Appendix C). The stimuli were coloured and shaded using Google Sketch-up 6. As in Experiments 1 and 2, images were captured of each object from an isometric perspective on a white background.

Design

The design was a 2 (Decision: Same vs. Different) x 2 (Feature: Form vs. Colour) nested factor design with Feature pertaining only to the different trials. Decision and Feature were randomized (without replacement) and mixed within a block with the constraint that half of the trials were the same and half were different. For the different trials, half of the objects had a different form (but the same colour) and half of the objects had a different colour (but the same form). There were a total of 16 practice trials and 648 experimental trials. The 324 "Same" trials were created by pairing the 81 unique objects with themselves and presenting these pairings four times over. The "different" experimental trials were comprised of 162 "different-form" trials (created by pairing the same colour with two randomly chosen, but different, forms) and 162 “different-colour” trials (created by pairing the same form with two randomly chosen but different, colours).

Procedure

The procedure was identical to Experiments 1 and 2.

Results

Reaction Times

RTs for accurate trials were subjected to the same recursive outlier procedure used in the previous experiments. This resulted in an elimination of 3.48% of the data. A one-way ANOVA yielded a significant main effect of Decision (Same vs. Different Form vs. Different Colour), F (2, 46) = 20.74, MSE = 855, $p < .001$, partial $\eta^2 = .47$. A post-hoc analysis using a Bonferroni adjustment for multiple comparisons revealed that participants responded significantly faster in the Same condition (M = 605 ms, SE = 24) than in both the Different Form condition (M = 654 ms, SE = 25) and the Different Colour condition (M = 649 ms, SE = 25). However, there was no significant difference between the latter two conditions, $p > .05$. These data are shown in Figure 5.

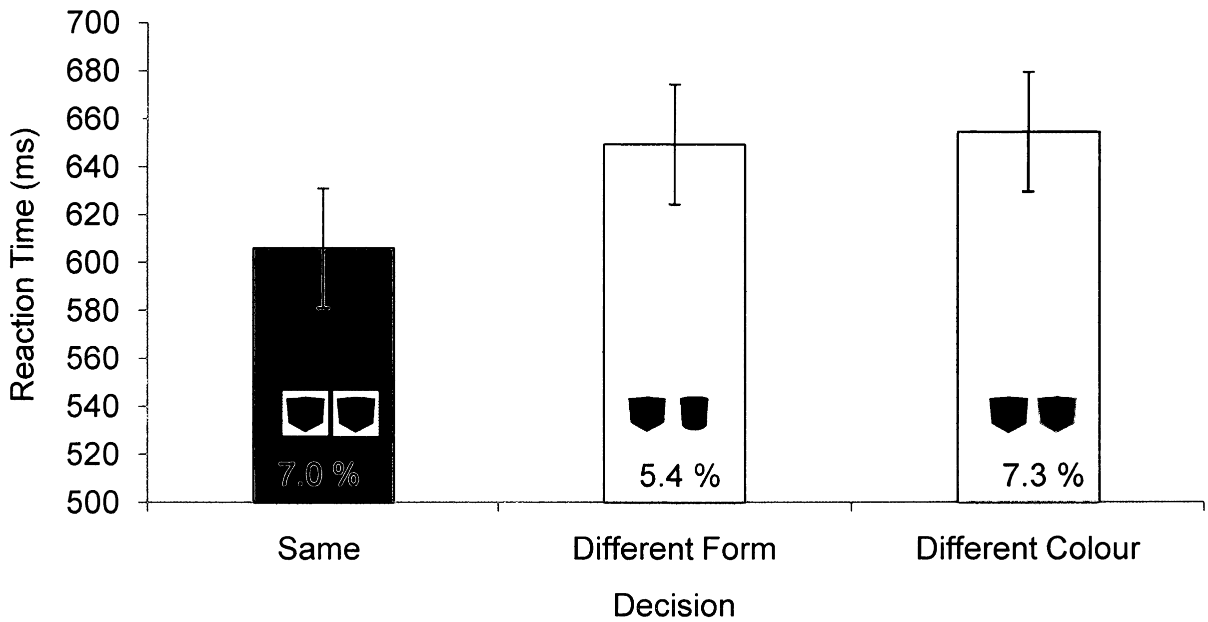

Figure 5. E3. Reaction times and error rates as a function of decision with standard error bars and examples of each condition.

Errors

No participants' mean error rate was more than 3 standard deviations above or below the mean error rate for each condition, thus the data from all participants were included in this analysis. A one-way ANOVA revealed no main effect of Decision (Same vs. Different Colour vs. Different Form), F (2, 46) = 2.18, MSE = .002, $p > .05$, $\eta_p^2 = .09$.

Discussion

The RT data indicated that there was no difference between the Different Colour and Different Form conditions. The fact that there was no main effect of Decision in the accuracy data provides further support for the claim that these nine colours and nine forms are equally discriminable across dimensions, even when presented as combined features. It should be noted, however, that a linear contrast on the accuracy data revealed that there were more errors in the Different Colour condition (M = 7.3 %, SE = 1.1 %)

than in the Different Form condition (M = 5.4 %, SE = 1.2 %), F (1, 23) = 5.67, MSE = .001, $p < .05$, partial $\eta^2 = .20$. This linear contrast analysis effectively ignores the contribution of the Same condition (50% of the trials) to the results, thus the significance of this post hoc analysis in relation to the main finding of no difference between the Different Colour and Different Form conditions should be interpreted with caution.

Given that it has now been established that these nine colours and forms are perceptually equally discriminable between dimensions, whether they be presented separately (Experiment 2) or combined (Experiment 3), this stimulus set will be used in Experiment 4 to explore whether any differences between colour and form information are observed at higher-order levels of processing (e.g., storage and retrieval).

Experiment 4

The objective of Experiment 4 was to assess whether form information is *remembered* better than colour information, even though these features have been equated perceptually. That is, form may be more important than colour for object recognition (e.g., Biederman's RBC theory), which is likely to rely on the formation of stable and enduring representations, whereas the perceptual matching task (used in Experiments 1, 2 and 3) may rely on transient percepts. Thus, if there are any memory differences between form and colour information in Experiment 4, they cannot be attributed to perceptual level differences in the stimuli and must be due to higher-order (e.g., recognition, memory) processing.

Experiment 4 assessed memory for objects that varied as combined features (i.e., Colour x Form) as well as objects that varied along separate dimensions (i.e., Different Form, Different Colour) (Colour x Form). This paradigm provides two ways of investigating memory for form and colour. First, the types of errors (i.e., colour, form) made in the Colour x Form condition could be examined to make inferences about the relative strength in memory for forms and colours. Second, the separate feature conditions can be compared to determine if there are any differences in memory for form and colour when only one feature varied. It was anticipated that a memory advantage for one feature over another would be reflected in the results when features are both separate and combined.

It was predicted that participants would require more trials to learn the objects in the Colour x Form condition than in either the Different Colour or Different Form conditions because the objects in the Colour x Form conditon differ along two feature dimensions whereas the objects in the other two conditions only differ along one dimension. As such, there are twice as many features to remember in the Colour x From condition (see Figure 9). Furthermore, although Wheeler and Treisman (2002) assert that features from separate dimensions (i.e., form and colour) are stored in parallel and do not compete for storage, the nine objects in the Colour x Form condition were created by crossing three forms with three colours and therefore have more representational overlap. That is, there is neither a colour nor a form that is unique to any given object in the Colour x Form condition. This duplication of features across objects is likely to create interference in the acquisition of object locations through the incorrect pairing of forms and colours.

If, as it is argued here, previous findings of better memory for form than for colour are due to forms being more perceptually discriminable than colours, then using colour and form stimuli that have been equated for percpetual discriminability should yield no difference in the types of errors (i.e., colour vs. form errors) made in the Colour x Form condition. This finding would suggest that memory errors when a whole object (both colour and form) is forgotten, or if stored independently, both features are equally likely to be forgotten. Further, if these forms and colours are acquired and stored in memory with equal strength and are subject to the same rate of decay, then there should be no difference in error rates between the Different Form and Different Colour conditions.

However, if the pattern of preferential memory for form over colour, as observed in other experiments (e.g., Brown et al., 2007) was not an artifact of differences in perceptual discriminability, but is rather the result of faster acquisition and / or stronger representation of form information over colour information, then a different pattern of results is anticipated. Specifically, if form memory is better than colour memory, fewer trials would be required to complete the Different Form condition than the Different Colour condition. Further, the error rates in the Colour x Form condition should mirror the findings reported by Brown et al. (2007), Mitroi (2008) and Monkman et al. (2007). That is, there will be more colour errors than form errors in the combined (Colour x Form) condition (see Figure 12).

Method

Participants

Twenty-five Carleton University undergraduate students participated for course credit (9 males, 16 females).

Materials

The virtual environment used to display the to-be-remembered objects was created using Crytek's software engine, which underpins the Crysis gaming platform. The VE's four walls were modelled as a dark stone texture that diffusely reflected some of the overhead light. The floor was modelled as a grassy texture (see Figure 6). There were no distinguishing features in the room; all four walls were identical save for the numerical labels “1”, “2”, “3”, and “4”, which were at eye-level. At least one numerical label was visible from any viewpoint within the room. The numerical labels provided reference points for the memory test (see Figure 7). The 81 unique objects from Experiment 3 were used here and scaled such that they were clearly visible and distinguishable from each other. Nine objects, each subtending vertical and horizontal visual angles of approximately 2.3 degrees each, were positioned from an isometric perspective on identical brown tables evenly spaced around the room’s perimeter. The VE was viewed on a Samsung SyncMaster 2443 BW 24” widescreen LCD monitor at a resolution of 1920 x 1200 pixels. The display was slaved to a Dell Studio XPS 435T desktop computer, powered by an Intel Core I7 2.67 GHz processor with 6 GB of RAM, running Windows Vista Home Premium 64 BIT Editions with Service Pack 1. Participants used a standard mouse (by sliding it) to mimic head rotations and clicked the left mouse button to move forward and the right mouse button to move backwards in the direction they were currently facing, although only head rotations were necessary to view all nine objects.

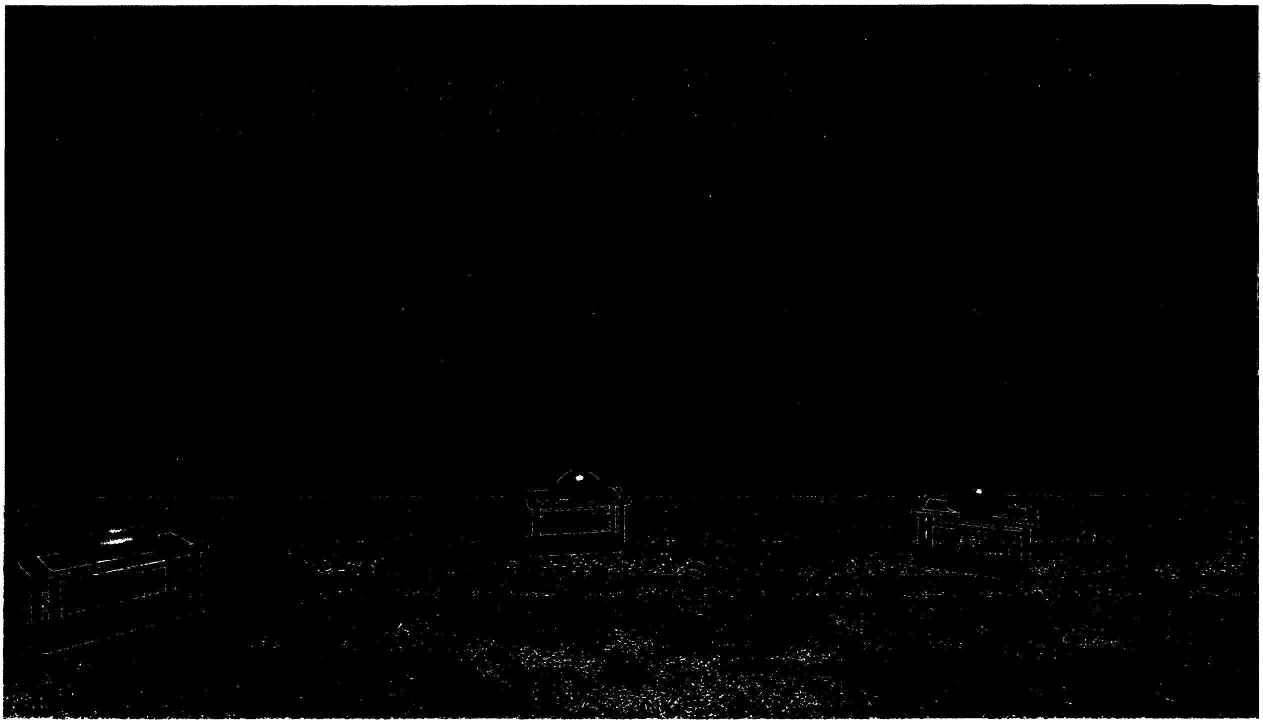

Figure 6. Image of the virtual environment from the Colour x Form condition of Experiment 4.

A 15-inch Macbook computer was used to randomly select objects and allocate them to one of the nine tables in the room. Thus, each participant had a unique array in each condition. This computer also logged participant responses using a custom designed response interface created using Microsoft C# programming language. Participants responded using a standard mouse to select and "drag" objects onto demarcated positions (see Figure 7). Only the nine the objects appearing in the VE were randomly positioned on the display interface, on the right side of the screen and oriented vertically.

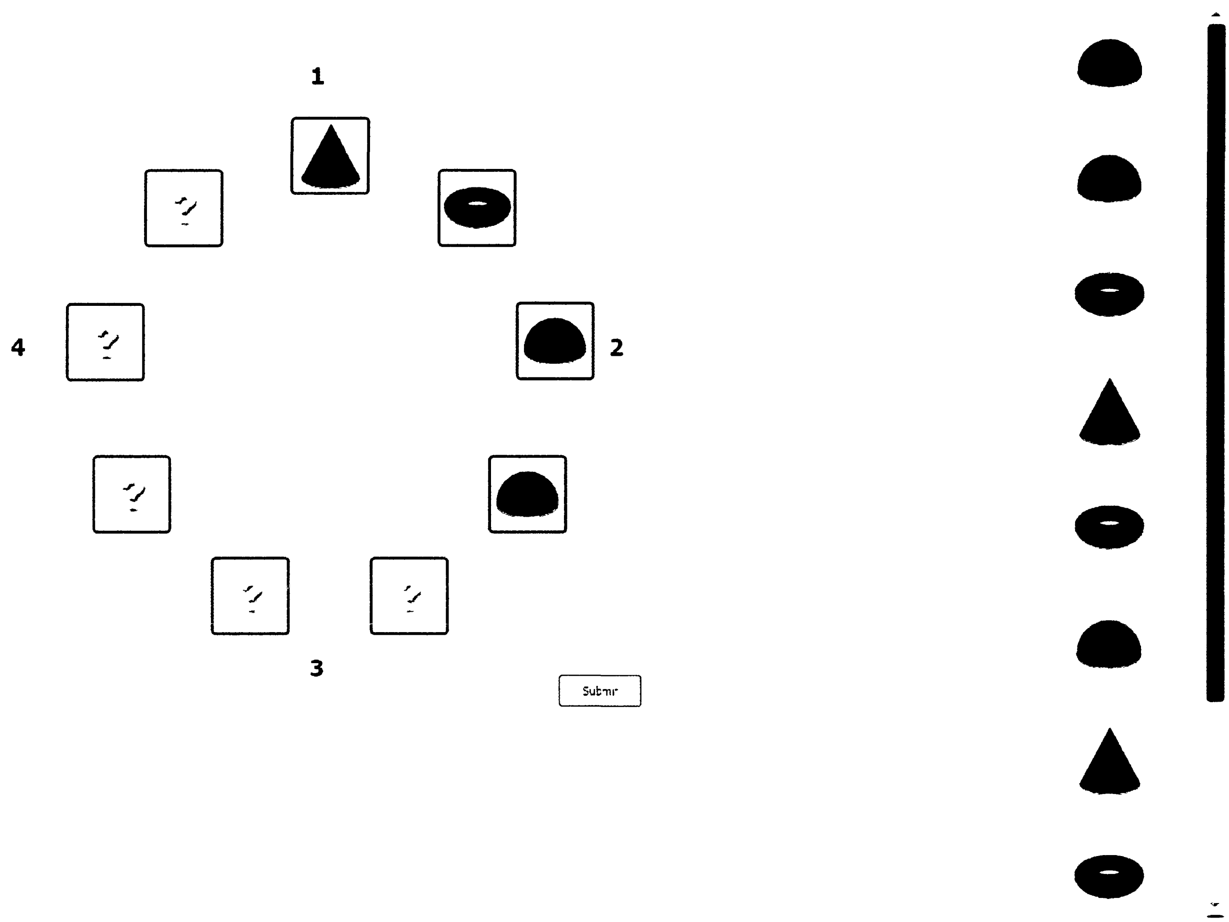

Figure 7. Example of the response interface in the Colour x Form condition in Experiment 4

Design

The design was a one factor with four levels (Feature Type: Different Form vs. Different Colour vs. Colour x Form vs. Colour x Real Object). Randomly selecting a single colour and assigning each of the nine forms to the locations created the objects in Different Form condition (see Figure 8). Similarly, randomly selecting a single form and randomly assigning each of the nine colours to the locations created the objects in the Different Colour condition (see Figure 8). Three randomly selected forms crossed with three randomly selected colours created the nine objects in the Colour x Form condition.

The Colour x Real Object condition was included to test a separate hypothesis and will therefore not be discussed further. The four conditions were counterbalanced across participants using a Latin-squares design.

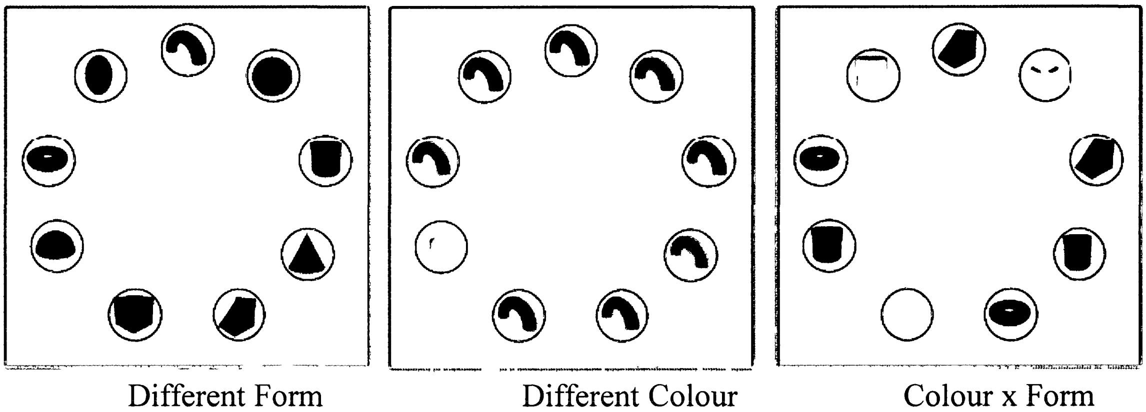

Figure 8. Examples of the objects in the Different Form, Different Colour and Colour x Form conditions in Experiment 4

Procedure

Prior to the beginning of the experimental phase, the experimenter ensured that the participant understood the task instructions and then had them complete a practice trial to familiarize themselves with the VE and the interface used to control their movements. The practice trial was the same duration as the experimental trials (45 s) so as to provide participants with an expectation for the length of the experimental trials. The practice VE was identical to the experimental VE, except that the objects were not visible. The experimenter instructed the participants to note the numbered labels on the four walls during the practice trial. Participants always started an experimental trial centered in the room, facing wall "1." Participants explored the room for 45 s, at which point the computer monitor was blanked.

Participants then turned to the response interface (see Figure 7) computer. There was no time limit for responses, nor were participants forced to make a response (they could leave a space blank if they chose to do so). Participants could change a response by dragging another object onto the desired placeholder to replace the previous object. Objects remained visible on the selection menu such that the same object could be placed in multiple locations if the participant chose to do so. Participants clicked the submit button to finalize their response. The program provided immediate feedback informing the participant that they did or did not correctly place all nine objects. If the participant made an error, another 45 s exploration trial began. This process continued until the locations of all nine objects were correctly recalled on two consecutive trials. This ensured that the participant did not correctly guess the object locations by chance.

Results

Trials to Complete

The data from one participant were removed from the subsequent analyses because he was unable to complete the task. Considerable discrepancies in the variances of the conditions were reflected by a violation of sphericity, as indicated by a significant Mauchly test, $\chi^2(2) = 12.06$, $p = .002$. A Greenhouse-Geisser adjustment was therefore adopted. The one-way ANOVA revealed a significant main effect of Feature (Different Colour vs. Different Form vs. Colour x Form), $F\,(1.39, 32.03) = 4.61$, $MSE = 6.93$, $\eta_p^2 = .17$, $p < .05$.

A linear contrast indicated that the Different Form ($M = 2.96$, $SE = .29$) condition required fewer trials to complete than the Different Colour ($M = 4.67$, $SE = .72$) condition, $F\,(1, 23) = 4.78$, $MSE = 7.33$, $p < .05$, partial $\eta^2 = .17$, when the influence of the Colour x Form condition was excluded. Additionally, as indexed by a quadratic contrast analysis, participants required more trials to complete the Colour x Form (*M* = 4.58, *SE* = .43) condition than the weighted average of the Different Form and Different Colour conditions, $F(1, 23) = 4.08$, $MSE = 2.33$, $p < .01$, partial $\eta^2 = .15$. However, a Bonferroni adjustment to control for multiple comparisons showed that the Different Form condition required significantly fewer trials to complete the than the Colour x Form condition and that the Different Colour condition was not significantly different from either the Different Form or Colour x Form conditions (see Figure 9).

Further inspection of the data revealed that the Different Colour condition was bi-modal in nature. Specifically, 20 participants completed the Different Colour condition in fewer than five trials and the remaining four participants required ten or more trials. Only the Different Colour condition produced this bi-modal distribution.

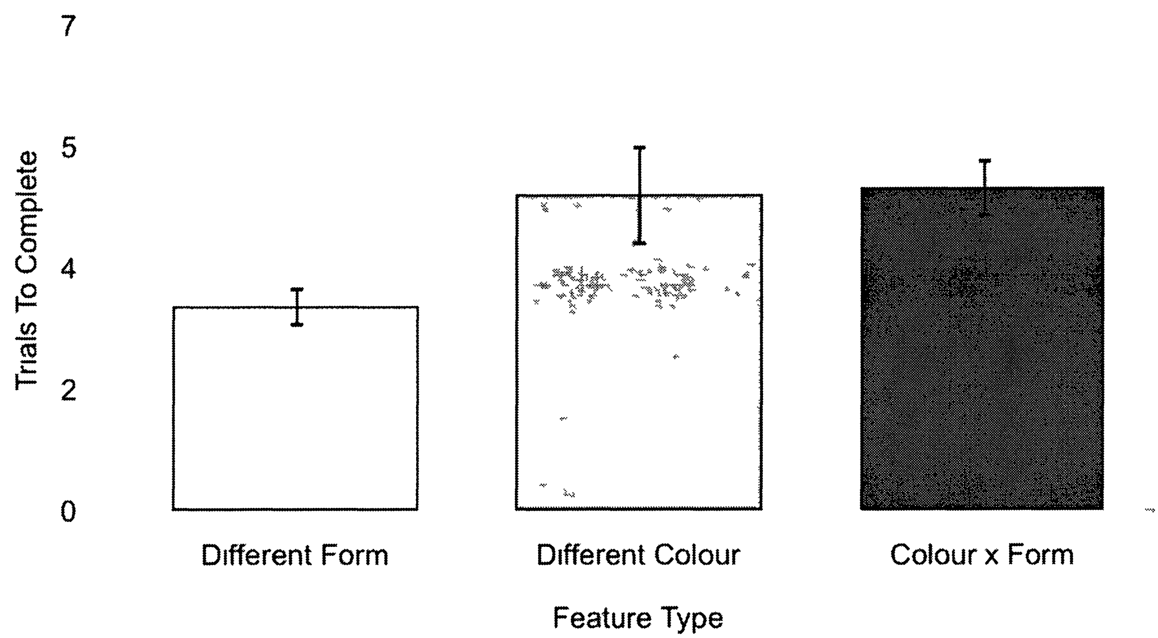

Figure 9 Average number of trials to complete as a function of Feature Type with standard error bars.

Form vs. Colour Errors

Because only one type of error can be made in the separate feature conditions (i.e., a colour error in the Different Colour condition or a form error in the Different Form condition), and two types of errors can be made in the combined feature (Colour x Form) condition, the separate conditions were analyzed independently from the combined condition. Participants made fewer errors in the Different Form condition ($M = 7.8$ %, $SE = 2.1$ %) than in the Different Colour condition ($M = 14.3$ %, $SE = 2.7$ %), $t\,(23) = 2.07$, $p = .05$ (see Figure 10). Critically, no differences between the likelihood of making a colour error ($M = 13.3$ %, $SE = 2$ %) and making a form error ($M = 14$ %, $SE = 2$ %) within the Colour x Form condition was found, $t < 1$ (see Figure 11).

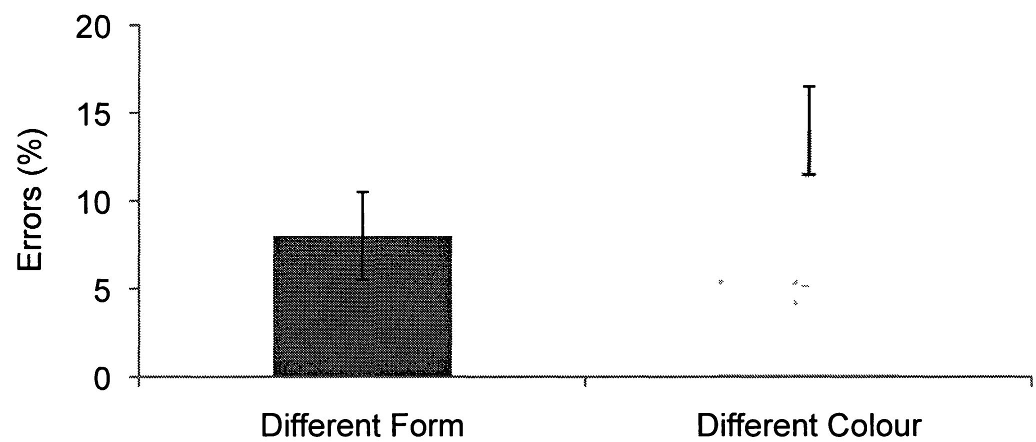

Figure 10. Errors for the separate feature conditions.

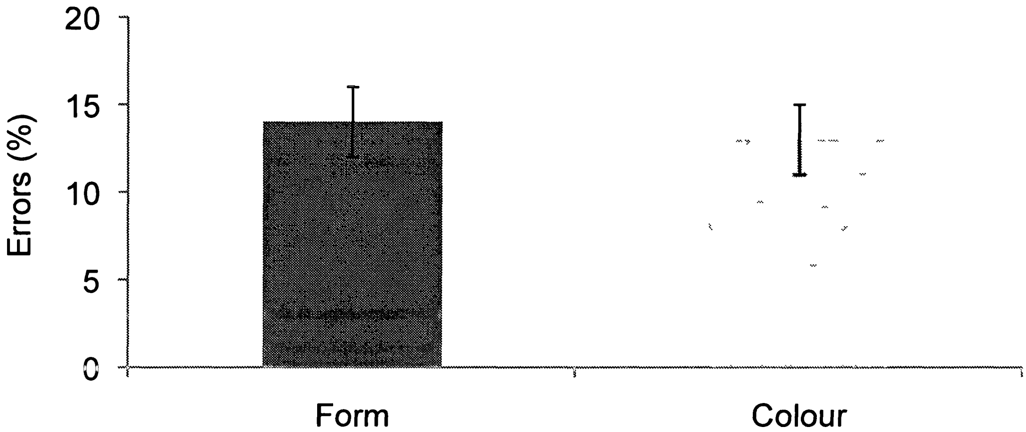

Figure 11. Form and colour errors for the combined (Colour x Form) feature condition.

Mitroi (2008) reported that differences in memory for form and colour were most pronounced at the beginning of the experiment, thus a similar analysis was conducted to determine if Experiment 4 produced the same pattern of data. Given that Mitroi (2008) did not have a separate features condition in her experiments, only the combined feature (Colour x Form) condition will be analyzed here. Only the first three trials were explored in the following analyses, as several participants completed each condition in less than three trials. Although no differences were found between the probability of making a form error ($M = .14$, $SE = .02$) and a colour error ($M = .13$, $SE = .02$) in the Colour x Form condition ($t < 1$), it is possible that the likelihood of making these two types of errors reversed after a few trials had elapsed, thus producing (statistically) identical error rates. Thus, a (Feature: Form vs. Colour) x 3 (Trial: 1 vs. 2 vs. 3) repeated-measures ANOVA was conducted. This analysis did not yield a main effect of Feature, $F < 1$. Not surprisingly, there was a significant main effect of Trial, F (1, 46) = 14.49, $MSE = .05$, $\eta_p^2 = .34$, $p < .001$. Furthermore, the Feature x Trial interaction was not significant, $F <$ 1. Thus, there was no evidence that the types of errors made (colour vs. form) drastically changed in likelihood as the experiment progressed.

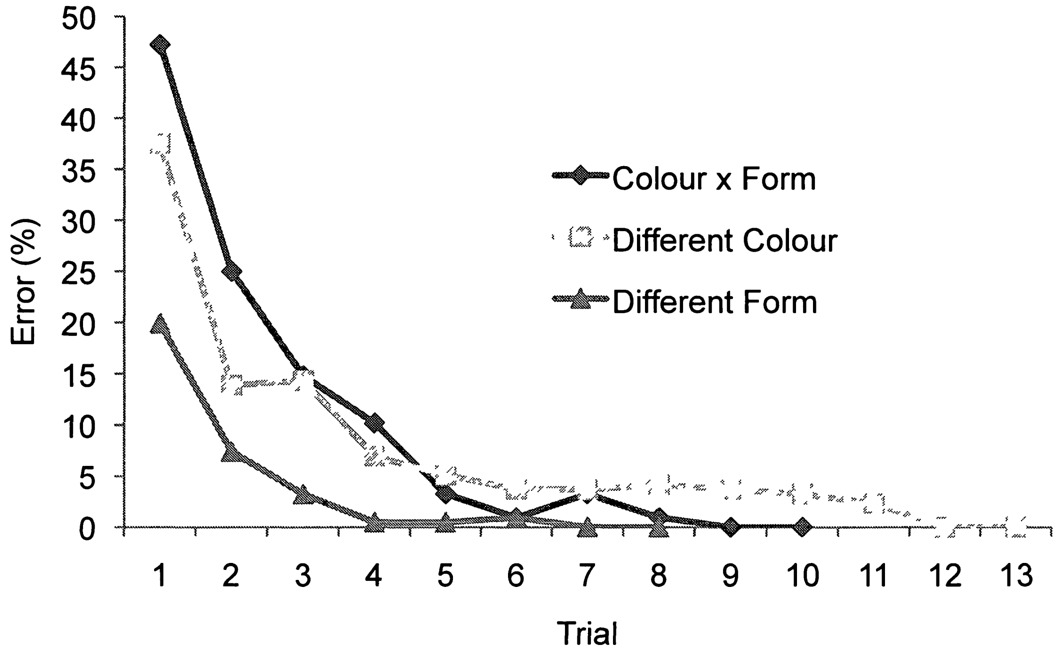

Figure 12. Percent error as a function of Trial and Feature Type.

The relationship between Feature Type and the spatial location of the stimuli was assessed in a separate analysis. Although there was evidence that participants made fewer errors on the three objects that were immediately visible at the onset of each trial, this did not interact with Feature Type[1]

Discussion

The critical finding from Experiment 4 is that the likelihood of making a colour error was statistically identical to that of making a form error in the combined (Colour x Form) feature condition. This finding indicates that, once equated for perceptual discriminability, memory for an object's form and its colour are equivalent, at least when experienced in the context of a VE. Thus, the results from the current investigation are

[1] A more detailed account of this analysis appears in Appendix H

inconsistent with previous reports of better form memory than colour memory for objects learned in a VE (i.e., Brown et al. 2007; Mitroi, 2008; Monkman et al., 2007).

The hypothesis that the duplication of forms and colours across objects in the Colour x Form conditon would interfere with learning was supported. More trials were required to complete the Colour x Form condition than either of the separate features (i.e., Different Form and Different Colour) conditions. However, given the amount of variability in the Different Colour condition, it is difficult to generalize this pattern of results. Surprisingly, it appears that, for some particiants, it was more difficult to learn the nine different colours in the Different Colour condition than the 18 features (one colour and one form for each of the nine objects) in the Colour x Form condition.

Although equated for perceptual discriminability, the nine colours in the Different Colour condition were more difficult to learn (i.e., more trials to complete and higher error rates) than the nine forms in the Different Form condition. This result may be due to the preferential encoding or slower decay of form information from memory, at least when form information is experienced separately from colour information. Interestingly, this bias for form over colour information was not paralleled in the Colour x Form condition – form and colour information were remembered equally well. This discrepancy between memory for colour and form information when experienced as separate or combined features may be attributable to the fact that only three colours and three forms were selected in the Colour x Form condition, whereas all nine colours/forms were used in the separate conditions. It is possible that discriminability differences between form and colour only emerge when many (i.e., more than three) features must be compared.

General Discussion

The purpose of this set of studies was to explore whether differences in memory for form and colour exist when perceptual discriminability has been equated between feature dimensions (i.e., form and colour). Experiment 1 showed that subjectively selecting colours and forms does not necessarily result in stimuli that are perceptually equally discriminable. This finding was indexed by significantly higher error rates for colours than for forms. Although the colours selected could be easily discriminated when presented simultaneously to the experimenter, their differences were not successfully discerned under the speeded timing parameters of the perceptual discrimination paradigm used in Experiment 1. Hence, previously reported differences in object recognition performance may be attributable to perceptual-level phenomena and not to higher order cognitive processing. However, once the original set of stimuli were reduced and re-tested using the same perceptual discrimination paradigm in Experiment 2, both reaction times and error rates for forms and colours were statistically equivalent. Thus, the nine forms and colours selected for Experiment 2 were equally discriminable within their respective feature dimensions. Subsequently, Experiment 3 demonstrated that the equal discriminability of these forms and colours persisted when these features were combined to form a single percept, as indicated by the RT data. These nine colours and nine forms were therefore deemed to be perceptually equally discriminable, when presented as separate or combined features.

Experiment 4 expanded on these perceptual-level findings by exploring the relative strength of these colours and forms in memory. The purpose was to establish whether previous findings of better memory for form than for colour (e.g., Brown et al., 2007) were due to the forms selected in these previous experiments being more perceptually discriminable than the colours. If there is evidence that the forms were more perceptually discriminable than the colours in these previous experiments, then there is doubt cast on the explanation that the reason why forms are remembered better than colour is because object recognition is form-based. Furthermore, by assessing memory for colour and form independently (in the separate feature conditions) it was anticipated that more evidence to support or refute preferential memory for form information could be found. If memory was better for form than for colour, then it should have been reflected for both separate and combined features. That is, there should have been fewer errors for the Different Form condition than the Different Colour condition *and* fewer form errors than colour errors within the Colour x Form condition. However, the pattern of results between separate and combined features was not similar.

The pattern of results from Experiment 4 was not consistent across the separate and combined feature conditions. There was no difference between the probability of making a form error or a colour error when form and colour were combined to create a single percept (i.e., the Form x Colour condition). This finding is inconsistent with other studies that used this same location memory paradigm (e.g., Brown et al., 2007; Mitroi, 2008; Monkman et al., 2007) in which the probability of making a colour error was significantly higher than making a form error. This discrepant finding is consistent with the hypothesis forwarded here that these previous studies used stimulus sets where the forms were more perceptually disciminable than the colours, which produced stronger/less confusable memory traces for the forms than the colours. Thus, previous conclusions that form information is inherently more memorable than colour information may have been premature.

However, if the forms and colours used in Experiment 4 were truly equal in their respective representational strengths, then both separate features conditions (i.e., Different Colour and Different Form) should have required fewer trials to complete than the combined condition. This result was only true for the Different Form condition. Contrary to expectation, the Different Colour condition required (statistically) the same number of trials to complete as the Colour x Form condition. This counterintuitive finding may have been driven by a small subset of the sample (4 of 24 participants) who required ten or more trials to complete the Different Colour condition when the rest of the sample requred five or fewer trials. In fact, these four participants found it so challenging to remember nine different colours that it was easier for them to complete the combined condition, where twice as many features had to be recalled. It therefore appears that some individuals rely on colour for identifying and remembering objects whereas, for others, colour may actually interfere with object memory, especially when the to-be-remembered colours are similar to one another. Further, given that this between-participant variability was observed in the Different Colour condition (nine colours) but not in the Colour x Form condition (three colours), storage capacity for colour may be variable across individuals, or smaller than that of form, at least for some individuals. Other possible explanation for the finding that the performance in the Different Colour condition was more variable than the Colour x Form is that some individuals are more sensitive to subtle colour differences or perhaps better at assigning verbal labels to colours. Thus, Experiment 4 provided evidence that colour memory is more variable than memory for form.

The results from Experiment 4 draw into question the claim that object recognition is purely form-based given that there are circumstances in which colour contributes to object recognition / memory. Instead, the finding that form and colour are remembered equally well when combined, is more aligned with Tanaka et al.'s (2001) "Shape + Surface" model of object recognition. In fact, the default may be for colour and form to contribute equally to object recognition but that one dimension dominates when the other has feature values with more overlap (i.e., less discriminable). In that vein, the colours selected in Biederman and Ju's (1988) may have had more featural overlap than the forms, thus object recognition was dominated by form information, resulting in no facilitation effects of coloured images over line drawings. Similarly, Wheeler and Treisman's (2002) colours may have been more discriminable than their forms, which led to improved accuracy in detecting colour changes than form changes.

The finding that colour information is remembered equally as well as form information when these two features are combined, but not when separated (in which case form is remembered better than colour) indicates that the utility of colour information in object memory is more variable than that of form. This supports Tanaka et al.'s (2001) assertion that form is the most reliable indicator of an object representation. Although many posit that colour vision evolved as a mechanism to assist in foraging for food amongst foliage (e.g., Mollon & Jordan, 1988; Regan et al., 2001), it also provides us with a variety of other opportunities to extract and respond to information from our environment. For instance, the colour of a traffic light indicates whether to accelerate or stop. However useful, colour information appears to be overshadowed by form information because colour tends not to be as reliable as form information for object identification. Form information defines the boundaries of an object and segregates it as a unique entity amongst other objects in complex environments. Thus, form is critical in the compartmentalization and comprehension of our surroundings. Colour can also be used to segment an object from its background, albeit to a lesser extent than form, and thus it is often used as a cue to demarcate an object's boundaries. In sum, form information is typically essential to recognizing objects whereas colour supplements this process, but is usually neither necessary nor sufficient. However, in order to be prudent, as Tanaka et. al. (2001) suggested, our object recognition system will make use of multiple features in order to maximize recognition accuracy under degraded viewing conditions. This redundancy principle has been observed for many years in many domains that convey visual information including road signage and commercial logos. For example, stop signs are recognizable by their octagonal shape and red colour. Thus, by combining more features to create unique representations, information is more likely to persist in memory.

Regardless of whether an experiment produces evidence that object recognition is form-based, colour-based, or (equally) form and colour based, it is imperative to equate lower-level perceptual influences to isolate the effects of higher-order cognitive processes such as object recognition and memory. The results of this set of experiments highlighted the importance of objectively equating the perceptual discriminability of forms and colours across dimensions, and the associated challenges therein, in order to draw conclusions about how colour and form contribute to memory for object identity.

Although efforts were made to be consistent across this set of experiments, there were some factors that were not controlled. For example, the background colours and textures were different in Experiment 4 than in Experiments 1 through 3 due to limitations of the software used to create the VE. Thus, it is possible that colour discriminability may be different in Experiment 4 than in Experiments 1 through 3 because the objects in Experiment 4 were presented against a differently coloured background.

Despite some of the limitations of this work, the 81 percepts developed and equated for perceptual discriminability in Experiments 1 through 3 can still be used to assess other experimental questions. It would be interesting to use this set of stimuli to determine whether Wheeler and Treisman's (2002) result (i.e., colour changes being detected more accurately than form chances) replicates once these features have been empirically equated for perceptual discriminability. Further, using these stimuli in an object location task similar to that used in Experiment 4 would also provide opportunity to assess whether forms and colours are still remembered equally well when the VE is populated with more objects that must be recalled. Additionally, it would be interesting to combine the location memory task used in Experiment 4 with either a verbal or visual secondary task in a dual-task working memory paradigm in order to determine if forms and colours have visual and/or verbal codes. Although only a few uses for the stimuli developed in this set of experiments have been discussed here, there are likely to be other questions in both fundamental and applied research that could be addressed by using features that have been equated for perceptual discriminability.

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Appendix A: Stimuli for Experiment 1

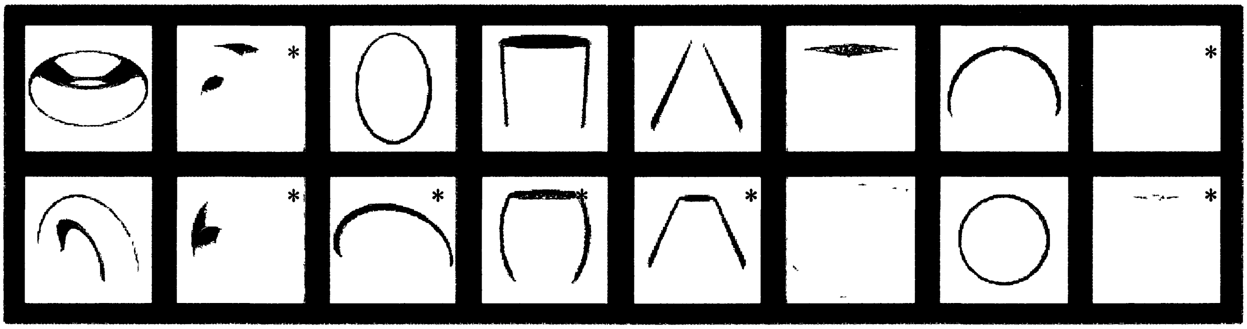


Figure 13. Forms used in Experiment 1

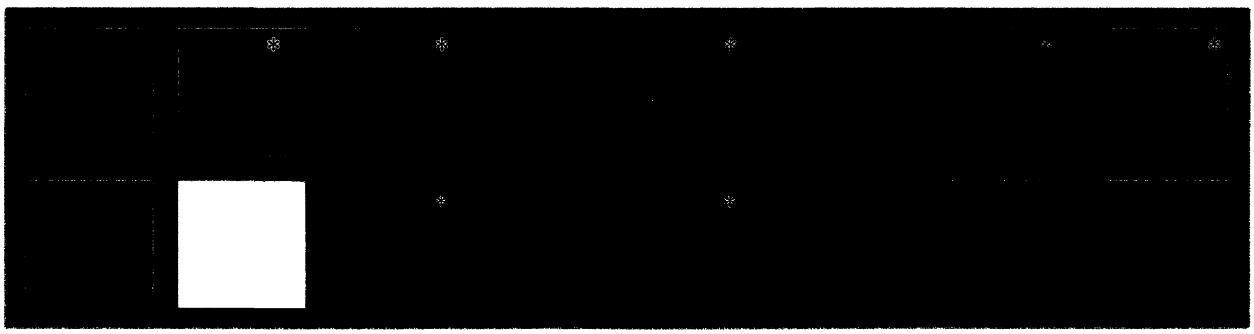


Figure 14. Colours used in Experiment 1

Note. * Denotes items that were removed from the stimulus set for Experiment 2.

Appendix B: Data From Experiment 1

Table 1

Reaction times and error rates for Experiment 1.

	Same Form *M* (*SD*)	Same Colour *M* (*SD*)	Different Form *M* (*SD*)	Different Colour *M* (*SD*)
RT (ms)	586 (121)	575 (132)	642 (134)	608 (118)
Error (%)	5.4 (5.2)	4.6 (4.3)	4.3 (2.9)	8.0 (2.3)

Appendix C: Stimuli for Experiment 2

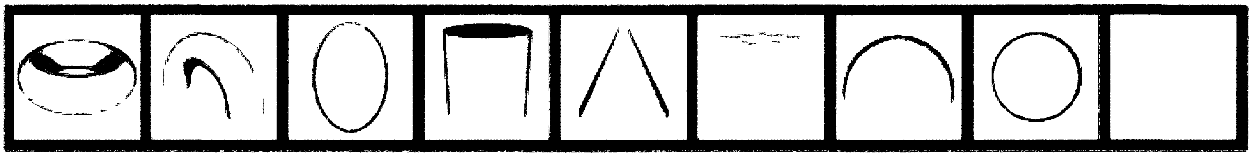


Figure 15. Forms used in Experiment 2.

Figure 16. Colours used in Experiment 2.

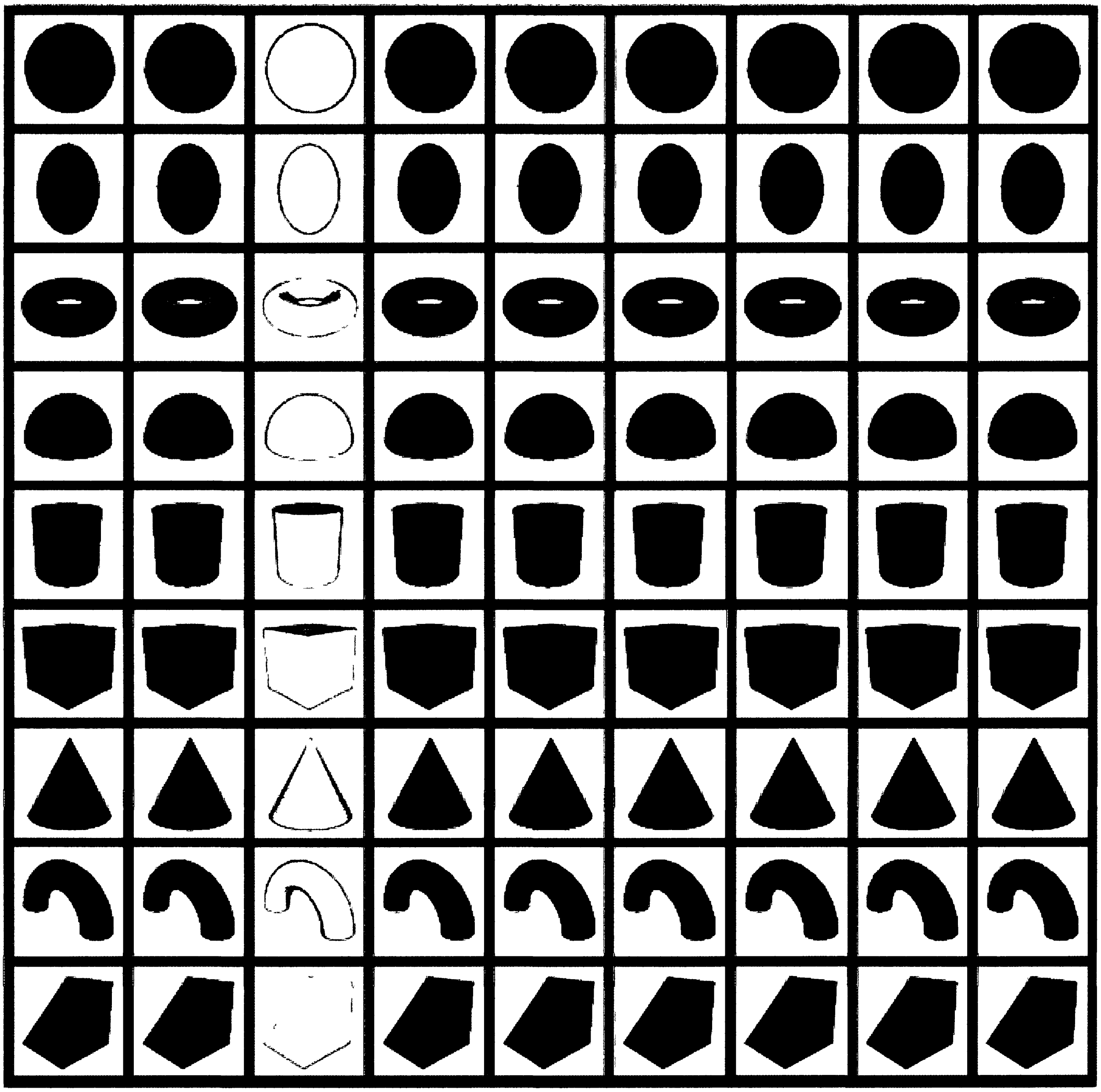
Appendix D: Data From Experiment 2

Table 2

Reaction times and error rates for Experiment 2.

	Same Form *M* (*SD*)	Same Colour *M* (*SD*)	Different Form *M* (*SD*)	Different Colour *M* (*SD*)
RT (ms)	613 (128)	626 (145)	647 (132)	654 (145)
Error (%)	4.7 (2.9)	3.9 (3.8)	2.6 (2.2)	3.5 (2.4)

Appendix E: Stimuli for Experiment 3



Appendix F: Data From Experiment 3

Table 3

Reaction times and error rates for Experiment 3.

	Same *M* (*SD*)	Different Form *M* (*SD*)	Different Colour *M* (*SD*)
Trials to Complete	604 (119)	654 (120)	649 (122)
Error (%)	7.0 (5.3)	5.4 (5.9)	7.3 (5.6)

Appendix G: Data From Experiment 4

Table 4

Trials to complete and error rates for Experiment 4.

	Different Form *M* (*SD*)	Different Colour *M* (*SD*)	Colour x Form *M* (*SD*)
Trials to Complete	2.96 (1.43)	4.67 (3.56)	4.58 (2.08)
Error (%)	7.76 (10.4)	14.26 (13.1)	19.38 (12.0)

Table 5

Error rates for the Colour x Form condition in Experiment 4.

	Colour Error *M* (*SD*)	Form Error *M* (*SD*)
Error (%)	13.58 (10.28)	13.34 (10.28)

Appendix H: Analysis of Errors as a Function of Position and Feature Type

A 3 (Feature Type: Different Colour vs. Different Form vs. Colour x Form) x 9 (Positions 1 through 9; see Figure 17) ANOVA revealed a significant main effect of Feature Type, F (2, 46) = 8.48, MSE = .09, $p < .001$, $\eta_p^2 = .27$. A Bonferroni adjustment to control for multiple comparisons revealed significantly fewer errors were made in the Different Form condition (M = 8 %, SE = 2 %) than the Colour x Form (M = 19 %, SE = 2 %) conditions. However, the Different Colour (M = 14 %, SE = 3%) condition was not significantly different from the other two conditions. Participants made fewer errors for objects that were in front of them when they started a learning trial (i.e., positions 9, 1 and 2) than behind them, F (8, 184) = 10.94, MSE = .02, $p < .001$, $\eta_p^2 = .32$. However, the Feature by Position interaction was not significant, F (16, 368) = 1.58, MSE = .02, $p > .05$, $\eta_p^2 = .06$.

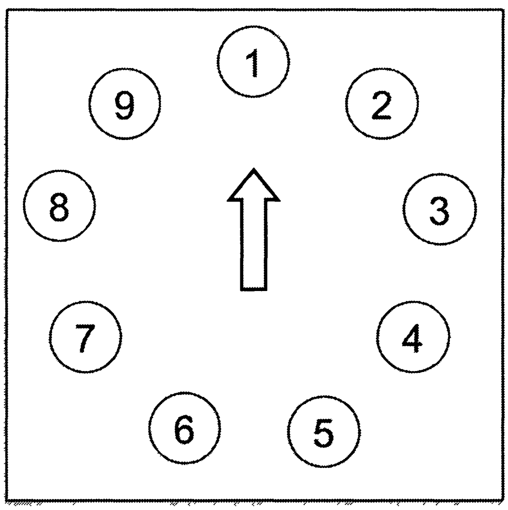


Figure 17. Index of object locations

Note. Arrow denotes the direction participants faced at the beginning of every trial.

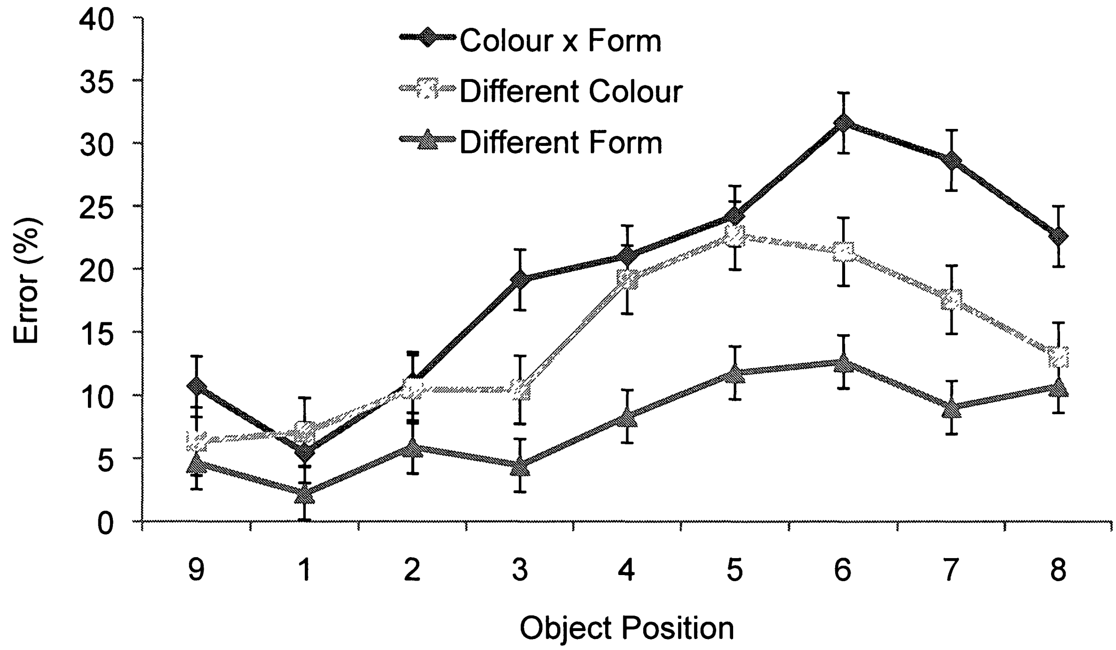


Figure 18. Percent error as a function of Object Position and Feature Type

Not surprisingly, participants made the fewest errors for objects in front of them. This finding may be due to the serial position effect and exposure. The serial position effect is the propensity for items at the beginning and end of a list to be remembered better than those in the middle of the list. Exposure plays a role in this finding because participants commenced each trial facing object number one (therefore with objects nine and two were in the field of view) and therefore saw these objects more than other objects (e.g., the ones behind them). In order to view objects other than nine, one, and two, participants had to rotate to orient the remaining objects into their fields of view. Thus, both increased exposure and primacy may have contributed to better acquisition of the objects in front of participants than the remaining objects.