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Haptic Concepts

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1. Introduction

A concept may be defined as a collection of objects grouped together by a common name whose members are usually, but not always, generated by a plan or algorithm. All words are concepts, as are the natural categories, esthetic style, the various diseases, and social stereotypes. In virtually all cases, an endless number of discriminably different examples of a concept has been rendered equivalent. A striking example was provided by Bruner, Goodnow, and Austin (1956), who noted that humans can make 7 million color discriminations and yet rely on a relative handful of color names. We categorize, according to Bruner et al., for a number of reasons – it is cognitively adaptive to segment the world into manageable categories, categories once acquired permit inference to novel instances, and concepts, once identified, provide direction for instrumental activity. For example, we avoid poisonous plants, fight or flee when encountering threat, and make decisions following a diagnosis. With rare exceptions, all concepts are acquired by experiences that are enormously complex and always unique.

However, the substantial and growing literature on formal models of concepts (e.g., Busemeyer & Pleskac, 2009) and the discovery of variables that shape concepts (e.g., Homa, 1984) has been acquired, almost exclusively, from studies that investigate the appearance of objects, i.e., the presentation of stimuli that are apprehended visually. Yet a moment's reflection reveals that our common concepts are associated with inputs from the various modalities. The taste, texture, odor, and appearance of food might critically inform us that this food is spoiled and not fresh; that the distinctive shape, gait, and sound marks this stray dog as probably lost and not dangerous; and the sounds, odors, and handling might be telling us that the family car needs a tune-up. Little is known about haptic or auditory concepts and virtually nothing is known about cross-modal transfer of categorical information between the different modalities, at least not from formal, experimental studies.

In contrast to the dearth of studies involving multimodal input and cross-modal transfer in category formation, there exists ample, albeit indirect, support for the role of multimodal properties revealed from other cognitive paradigms, ranging from feature and associative listing of words and category instances to the solution of analogies and logical decision-making. When asked to list attributes of category members (e.g., Garrard, Lambon, Ralph, Hodges, & Patterson, 2001; Rosch & Mervis, 1975), subjects typically include properties drawn from vision, audition, touch, olfaction, and taste. Similarly, the solution of analogies (e.g., Rumelhart & Abrahamson, 1973) and category-based induction (e.g., Osherson, Smith, Wilkie, & Lopez, 1990) involve properties reflecting the various modalities. More direct support has been obtained from motor control studies involving olfaction and vision (Castiello, Zucco, Parma, Ansuini, & Tirindelli, 2006), in which the odor of an object has been shown to influence maximum hand aperature for object grasping, and mental rotation of objects presented haptically and visually (Volcic, Wijnjes, Kool, & Kappers, 2010). Each of these studies suggests that our modalities must share a common representation.

1.1 Summary of proposed studies

In the present chapter, we report the results of experiments, including recent results from our laboratory, that explore whether concepts learned haptically or visually can transfer their information to the alternate modality. We also report whether categorical information, simultaneously perceived by the two modalities, can be learned when put into conflict. Specifically, the objects explored visually and haptically belonged to the same category but were, unbeknownst to the subject, different objects. In the latter situation, we are especially interested in whether intermodal conflict retards or even precludes learning or whether the disparities provided by touch and vision are readily overcome. We also report the results of a preliminary study that addresses whether concepts can be learned when partial information is provided. Finally, we explore whether the representation of categories acquired haptically or visually differ minimally or dramatically and whether the structures are modified in similar ways following category learning.

The lack of research into multi-modal concepts should not imply that little is known about haptic processing. The classic Woodward and Schlosberg (1954) text devoted a chapter to touch and the cutaneous senses, and a recent textbook on haptics (Hatwell, Streri, & Gentaz, 2003) lists 17 subareas of research with over 1000 references. There is now an electronic journal devoted to haptics (Haptics-e), the IEEE Transactions on Haptics was established in 2009, and numerous labs have been formed both nationally and internationally that are dedicated to haptics and haptic interfaces. A brief summary of pertinent research on haptic processing is presented first.

1.2 Brief summary of haptic processing

Haptic perception requires active exploratory movements derived from proprioceptive information. Unlike vision, which provides useful information from a single glance and at a distance (e.g., Biederman, 1972; Luck & Vogel, 1997), haptic perception relies on sequential examination in which tactile-kinesthetic reafferences can be generated only by direct contact with the stimulus. The absence of vision, however, does not preclude the coding of reference and spatial information (Golledge, 1992; Golledge, Ruggles, Pellegrino, & Gale, 1993; Kitchin, Blades, & Golledge, 1997). Haptic perception enables the blind to identify novel stimuli (Klatzky & Lederman, 2003), detect material properties of objects (Kitchin *et al.*, 1997; Gentaz & Hatwell, 2003; 1995), and to acquire abstract categories (Homa, Kanav, Priyamvada, Bratton, & Panchanathan, 2009). For example, we (Homa et al., 2009) demonstrated that students who are blind can learn concepts whose members vary in size, shape, and texture as rapidly as sighted subjects who were permitted to both touch and view the same stimuli. Interestingly, the blind subjects exhibited lower false alarm rates than normally-sighted subjects who were permitted to view and handle the stimuli or who were blindfolded and relied on touch alone, rarely calling ‘new’ stimuli ‘old’, but with one curious exception – they invariably false alarmed to the category prototypes and at a much higher rate than any other subjects.

Numerous studies have explored how shape (Gliner, Pick, Pick, & Hales, 1969; Moll & Erdmann, 2003; Streri, 1987), texture (Catherwood, 1993; Lederman, Klatzky, Tong, & Hamilton, 2006; Salada, Colgate, Vishton, & Frankel, 2004), and material (Bergmann-Tiest & Kappers, 2006; Stevens & Harris, 1962) are coded following haptic exploration. Researchers have embraced the possibility that learning and transfer are mediated by an integration of information from multiple sensory modalities (Millar & Al-Attar, 2005; Ernst & Bulthoff, 2004), and that visual and tactile shape processing share common neurological sites (Amedi, Jacobson, Hendler, Malach, and Zohary, 2001). Ernst and Banks (2002) concluded that the lateral occipital complex is activated in similar ways to objects viewed or handled. More recently, Ernst (2007) has shown that luminance and pressure resistance can be integrated into a single perception "if the value of one variable was informative about the value of the other". Specifically, participants had a lower threshold to discriminate stimuli when the two dimensions were correlated but not when they were uncorrelated.

1.3 Stimuli for Experiments 1-3

The initial studies used complex 3D shapes, shown in Figure 1, that were composed of three abstract prototypical shapes and systematic distortions. Objects were originally modeled in the Maya 3D modeling software produced by Autodesk. Initially, 30-40 3-dimensional virtual forms were generated using a shape growth tool within the Maya suite, and 20 were chosen for multidimensional scaling. Three forms were then selected from the multidimensional space (MDS) that were moderately separated from each other and which appeared to be equi-distant from each other in three dimensions. These 3 forms become the prototypical forms for three categories. The surface of each prototype was then subdivided into a very small polygon mesh which gives objects a more organic appearance.

The Maya's shape blend tool was used to generate forms that were incremental blends between all pairs of the 3 prototype forms. This resulted in a final category population of 24 3-dimensional objects, where each prototype was transformed, along two paths into the other two prototypes. The distortion setting used in the shape blend tool was set to .14, which allowed for 7 forms to be generated between each prototype pair. The forms were then converted from Maya's file format which could then be steriolithographically printed using a ZCorperation Zprinter. Each of the objects was smooth to the touch and of the same approximate weight and overall size.

1.4 Theoretical issues

This structure was selected to address a number of additional issues. First, each prototype occupied the endpoints of two transformational paths and was the only form capable of readily generating its distortions. However, unlike the vast majority of studies in categorization, each prototype was not otherwise central to its learning (or transfer) patterns but was positioned at the endpoints of two transformational paths. We were interested in whether these prototypical objects would, nonetheless, exhibit characteristics typically found in recognition and classification. For example, the prototype is often falsely recognized as an old pattern and classified better than other new exemplars (Metcalfe & Fisher, 1986; Nosofsky, 1991; Shin & Nosofsky, 1992). However, exceptions in recognition to this outcome have been obtained (Homa, Goldhardt, Burruel-Homa, & Smith, 1993; Homa, Smith, Macak, Johovich, & Osorio, 2001), apparently when the prototype is a unique pattern rather than composed of features identically contained in its exemplars.

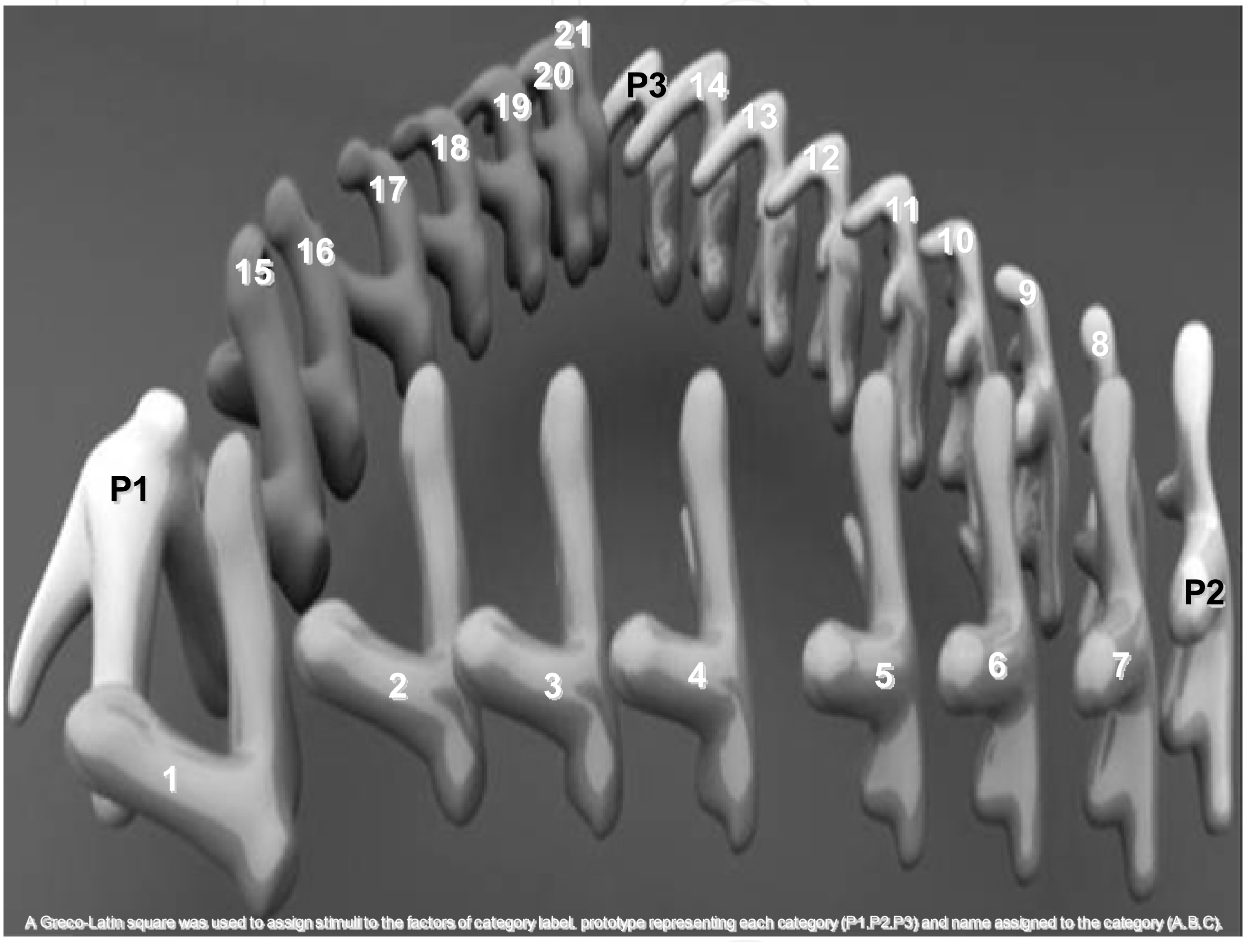

Fig. 1. The categorical space composed of 24 shapes; each category prototype is located at the vertex

In the present experiments, all objects including the prototypes were unique patterns, composed of novel and not identically repeated features or components. Second, two types of new patterns were used in transfer, those that were positioned between old training forms and those that were located at the midpoint of the transformational paths generated from different prototypes. In effect, each midpoint stimulus was a form that was positioned within a ‘gap’ that was positioned in the middle between two prototypes. We were interested in whether an object that fills a gap and flanked by two training patterns from different prototypes would be less likely to be falsely recognized as old than other new patterns that were similarly flanked by two training patterns but which was closer to the category prototype. If similarity to close training neighbors in learning dictates (false) recognition, regardless of the category membership of the neighbors, then recognition of the midpoint objects should be similar to recognition of the new objects. Alternatively, if ambiguity of category membership also plays a role, as well as similarity to old training objects, then (false) recognition should be reduced, compared to the new objects. This was because the midpoint objects could not be unambiguously classified into a single prototype, since either of two prototype classes would be correct.

2. Cross-modal category transfer

Experiment 1 examined visual (V) or haptic (H) category learning followed by a transfer test in the same or alternate modality (VV, VH, HV, HH). Half of the subjects received random or systematic training. Particular contrasts were of special interest: (a) Transfer differences between the VV and HH conditions should reveal whether visual concepts are learned better than concepts learned haptically; (b) VV vs. VH and HH vs. HV should indicate how much information is lost when tested in an alternate modality; and (c) VH vs. HV would indicate whether information is transferred more readily from one modality to the other.

2.1 Method

Objects were placed on a small table next to the participant. An opaque dark blue curtain was hung between the stimuli and participant and could be slid back and forth along a rod situated 10 feet above, allowing the participant to view or handle the object. This allowed the experimenter to select a designated stimulus to present to the subject, while hiding the remaining 23 stimuli. The stimuli were shown one at a time. Four types of objects can be identified: (a) 12 old objects, 4 from each category prototype, that were presented during learning; (b) 6 new patterns, 2 from each category; (c) 3 prototypes; and (d) 3 midpoint objects. The latter objects were midway between either of two prototypes and, therefore, could not be unambiguously assigned to a single prototype category. A schematic representation of the 24 objects, separated by the three categories and transformational paths is shown in Figure 2.

2.2 Procedure

The learning phase was composed of four study-test trial blocks. On each study block, the 12 learning objects were shown randomly or systematically blocked by category, labeled as A, B, or C for the subject. Following this, the objects were presented in a random order and required verbal classification of the object (A, B, or C). Following their judgment, corrective verbal feedback was provided. For subjects in the systematic condition, the three categories were presented in a counterbalanced order, although patterns belonging to a given category were shown in a random order.

On the transfer test, all 24 objects were presented in a random order, which included the four training patterns in each category (old), the three category prototypes, and nine new objects. As indicated in Figure 2, three of the new patterns were located midway between the two prototypes and were, as a consequence, analyzed separately from the remaining new objects. On the transfer test, the subject was required to make a double judgment to each object. The first judgment was a recognition judgment – is this object old or new? The second judgment was a classification judgment (is it an A, B, or C pattern?).

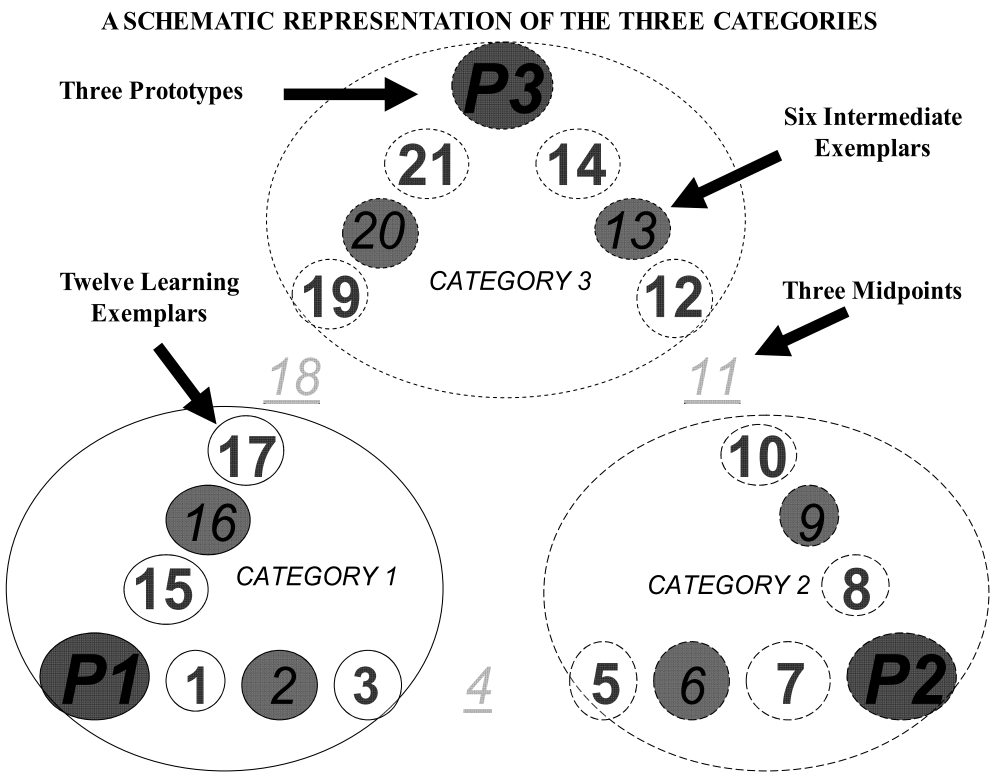

Fig. 2. A schematic representation of the three categories and 24 objects

2.3 Results - Learning

Figure 3 shows the mean correct classification rate across learning blocks as a function of input modality and training order (systematic, random). The main effects of learning blocks, modality of training, and order of stimulus presentation during learning were each significant.

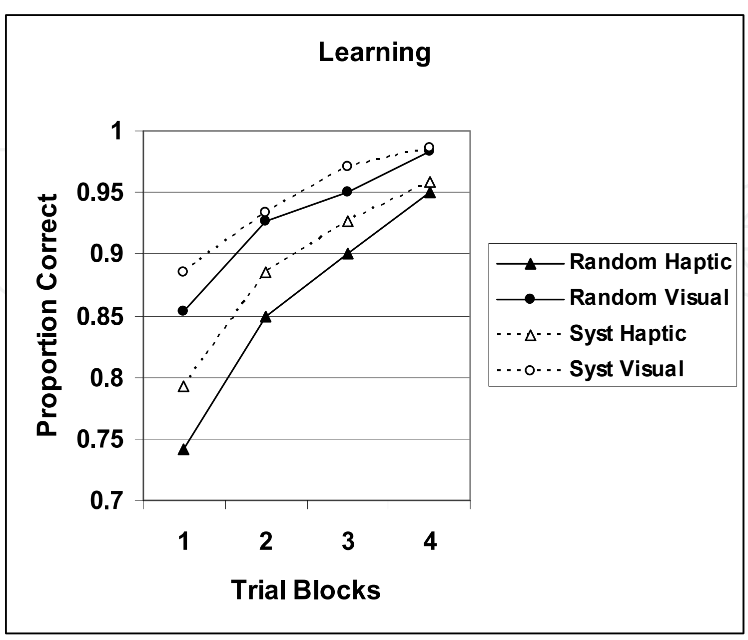

Fig. 3. Learning across training blocks as a function of modality and order of presentation.

In general, performance improved across learning blocks, learning was more efficient with visual than haptic inspection, and performance was enhanced when study presentation was systematic.

2.4 Results – Transfer classification and recognition

Classification errors were unexpectedly rare, with overall error rates ranging between 3-10% among the four modality conditions, with accuracy highest in the VV condition and worst in the HH condition (participants were also tested one week later, and performance deteriorated a slight 4%).

Figure 4 shows the mean hit and false alarm rates as a function of study and test modality (VV, VH, HV, HH), training order (random, systematic), and time of test (immediate, week delay). In general, subjects were able to discriminate old from new objects with fair accuracy, with an overall hit rate of .715 and a false alarm rate of .543. The conditions ordered themselves, from best to poorest old-new discrimination, as VV > VH = HH > HV, with a mean difference between hits and false alarms of .304, .176, .167, and .100, respectively.

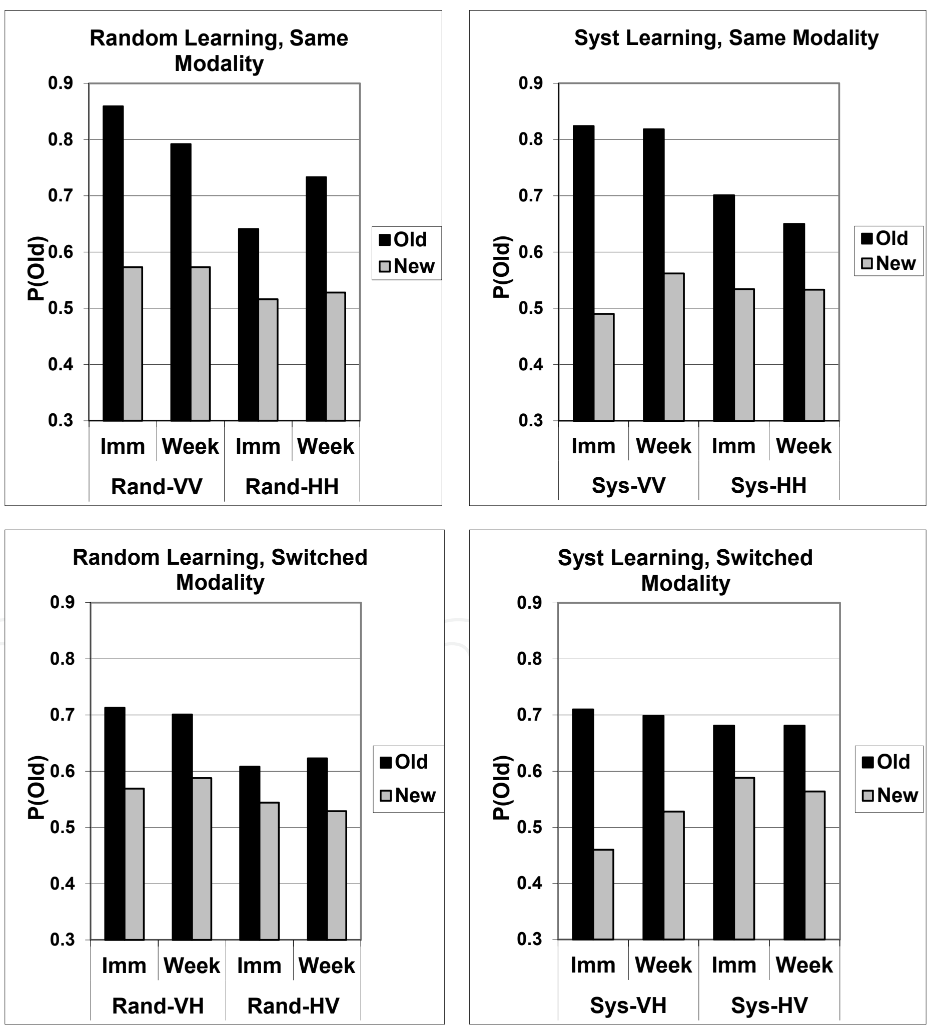

Fig. 4. Mean hit and false alarm rates as a function of study and test modality (VV, VH, HV, HH), training order (random, systematic), and time of test (immediate, week delay).

Testing in an alternate modality provides an index of level of transfer between these modalities. The overall level of discrimination between old and new objects was .304 for the VV condition versus .176 for the VH, which suggests that transfer was substantial but with some loss of information from the visual to the haptic modality. The HH/HV contrast provides an index of conceptual transfer from the haptic to the visual modality. The overall level of discrimination between old and new was .167 for HH; for HV, discrimination dropped to .100. Differences in performance between the HH and VH must reflect encoding (and transfer) from one modality to the other, given a common test modality. No overall differences in recognition discrimination emerged between these conditions (HH = .167; VH = .176), either as main effects or interactions. For the VV vs. HV condition, the difference in discrimination accuracy (VV = .304; HV = .100) was substantial.

In spite of the wide variations in transfer, each of the conditions – transfer to the same or alternate modality – revealed that the ability to discriminate old from new objects was significant even after a week delay. In particular, our expectation that discrimination in the alternate modality would vanish after one week was not supported.

Figure 5 shows the probability each object type (old, new, prototype, midpoint) was called old as a function of learning and transfer modality. In general, subjects were most accurate in identification of old patterns as 'old'; the midpoint, prototype, and new objects were (incorrectly) called 'old' at rates of .459, .539, and .586, respectively. A notable result was that the category prototype, often false alarmed at a higher rate than other new patterns (e.g., Metcalfe & Fisher, 1986), was incorrectly called 'old' no more often than other new objects. This replicates previous studies which have found that the prototype, when composed of continuously variable features, is likely represented as a novel, ideal pattern, not a familiar one (Homa et al., 1993; 2001).

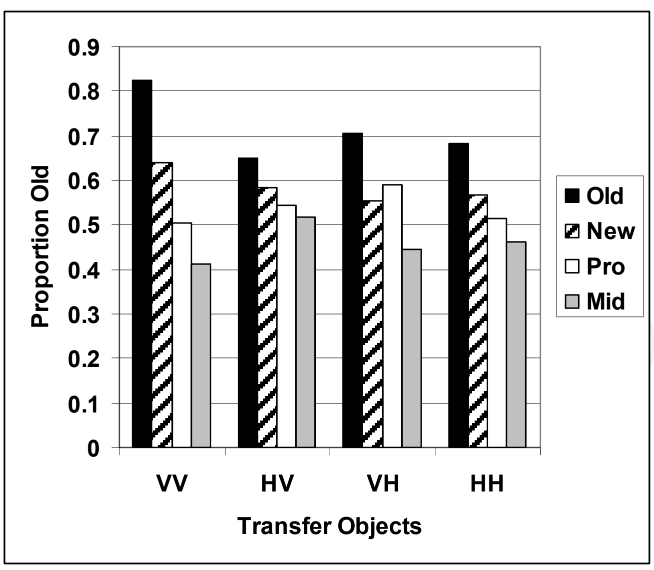

Fig. 5. Probability of calling a stimulus 'old' as a function of condition.

2.5 Conclusion

As expected, the categories were learned more rapidly when presented visually than haptically and when presented in a systematic rather than a random order. However, the terminal level of learning was virtually the same in each case. Surprisingly, classification on the transfer test, even when switched to a different modality, was remarkably accurate, with error rates ranging from 2-10%; the impact of a test delayed by one week was statistically significant but minimal in terms of absolute loss.

The greatest differences occurred in recognition, where again the visual modality generally resulted in superior performance. The visual-visual (VV) condition, compared to the haptic-haptic (HH) condition, revealed the general advantage of the visual modality for the same objects, and would be consistent with the general hypothesis that the visual modality encodes more (or more accurate) information than the haptic modality.

Recognition accuracy was slightly worse in the cross-modality conditions, with better discrimination found for visual study and haptic test than the reverse. This suggests that visual encoding provides considerably more information than haptic encoding, and that this difference remains even following haptic testing. A simple model is to assume that the visual modality encodes more features than does the haptic modality, and that each modality can transfer a proportion of these features to the alternate modality. For example, suppose that 80 features have been encoded and stored for each category following visual learning; for the haptic modality, 40 features are encoded. If 50% of all features can be transferred to the alternate modality, then the number of features available at the time of transfer would be 80(1.0) = 80 for VV, 80(.50) = 40 for VH, 40(1.0) = 40 for HH, and 40(.50) = 20 for HV, an ordering that matched that obtained in recognition.

3. Intermodal conflict in category learning and transfer

This experiment addressed whether categories can be learned when the objects, simultaneously explored visually and haptically, were actually different although from the same category. Following each study block, the subject was tested by presenting the study objects either visually, haptically, or both visually and haptically. This was repeated four times, followed by a transfer test similar to that used in Experiment 1.

One hypothesis is that cross-modal conflict should retard learning, because of the inconsistency of information available during study. Alternatively, presenting information that is available to both modalities, even when in conflict, could provide additional cues for learning. Since subjects were not told that the objects would be different, and since the differences among the patterns belonging to the same category were not strikingly obvious and encoded by different modalities, it is possible that the visually sensed and felt information for a given ‘stimulus’ might be integrated into a coherent percept. Since the features encoded visually and haptically could differ, at least for some percentage of the encoded features (Miller, 1972), any integration from the two modalities could, in principle, result in a more robust concept.

Alternatively, the subject could learn two versions for each category, one visual and one haptic, with integration between the modalities playing no role. It is worth stressing that the objects studied visually and haptically for each category were identical; only the pairing on each study trial was inconsistent. Since learning more categories has been found to retard learning but enhance later transfer (Homa & Chambliss, 1975), the formation of multiple-modality categories would predict that learning rate would be slowed by this manipulation but produce more accurate later transfer.

On the transfer test, subjects were either provided with the objects to be recognized and classified, based only on its visual appearance, from touch alone, or with both vision and touch provided. As was the case in learning, when an old object was presented to both modalities, the object matched its training pairing. Finally, as was the case in Experiment 1, objects were learned in a systematic or random manner, with testing occurring either immediately or after a delay of one week.

3.1 Method

The learning phase again consisted of a series of four 4 study-test trials with corrective feedback. On each learning trial, the participant visually perceived an object of a category (e.g., A1) and at the same time haptically explored, under an opaque black foam board, another object of the same category (e.g., A15). Presentation order for the systematic training condition again presented the objects blocked by category; in the random condition, category pairing was maintained but randomly selected in terms of the category presented. Following a given study block, the objects were randomly presented and the subject was asked to identify the category. In the visual condition, the objects were presented visually but could not be touched; in the haptic condition, each object could be manipulated but not seen. In the visual + haptic condition, the objects could be inspected both visually and haptically. Following each response, corrective feedback was provided. This procedure was repeated 3 additional study/test times. Participants were only informed of a category label and told to form each category by using both the appearance and felt conformations of each presented object. Participants were instructed to haptically explore and visually perceive the two conflicting stimuli simultaneously.

The transfer phase began either immediately or one week after completion of the learning phase. Participants were instructed to classify each object to its appropriate category learned during training (A, B, or C), and recognize whether this object was old or new using vision only, touch only, or both vision and touch. To each randomly presented object, participants gave a double-response after each presentation, recognition (Old or New) followed by classification (A, B, or C). Response time was self-spaced but restricted to 15 sec and feedback was not given during transfer test.

3.2 Results – Learning

Figure 6 shows the mean accuracy across learning blocks as a function of order of presentation and modality of test following each study trial. The main effect of learning blocks, order, and modality at test, were significant. In general, performance improved across learning blocks, with systematic presentation again facilitating rate of learning. Learning following visual + haptic test produced faster learning than visual alone or haptic alone ($p < .05$ in each case, Bonferroni test); visual alone also resulted in significantly fewer errors than haptic alone.

3.3 Results – Classification and recognition

Classification errors were again rare, averaging between 2% on the immediate test following systematic training and visual testing to 11.0% on the delayed test following random training and a haptic test.

On the recognition, test, the overall hit and false alarm rates were .794 and 533, respectively, which demonstrated that subjects discriminated old from new objects on the transfer test. The best discrimination occurred when recognition was tested visually (P(Hit) = .860, P(FA) = .532), or when both haptic and visual information were available (P(Hit) = .819, P(FA) = .468); when tested by the haptic modality alone, the difference between hits and false alarms remained significant but the level of discrimination was reduced (P(Hit) = .702, P(FA) = .600). A post-hoc Bonferronni test revealed that recognition discrimination was ordered V+H = V > H. Discrimination between old and new objects was also enhanced by systematic presentation during study, P(Hit) = .791 and P(FA) = .502; following random presentation, these values were P(Hit) = .796 and P(FA) = .565.

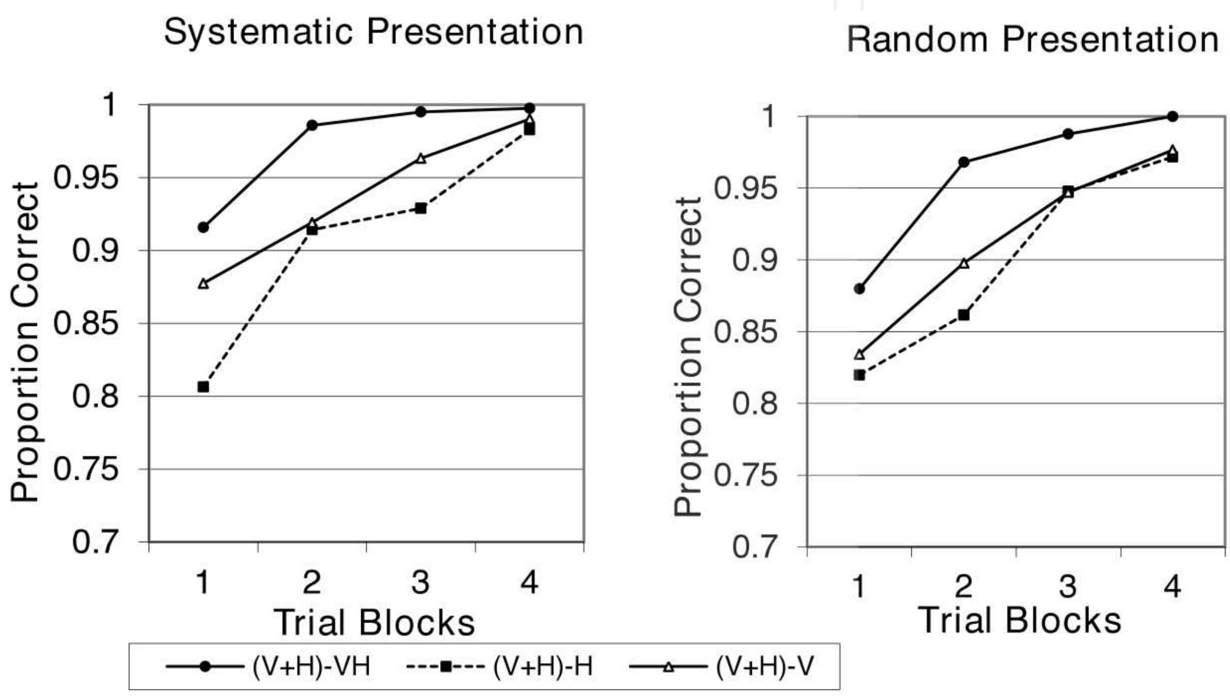

Fig. 6. Mean learning rate across trial blocks under conditions of cross-modal conflict

3.4 Discussion

Classification errors were again rare, averaging between 2% on the immediate test following systematic training and visual testing to 11.0% on the delayed test following random training and a haptic test.

Inter-modal conflict neither retarded learning nor degraded recognition. In fact, learning was speeded slightly by intermodal conflict, with learning rates comparing favorably to those obtained in any of the conditions in Experiment 1. Similarly, classification and later recognition was largely unperturbed by this manipulation. The results do show clear dominance by the visual modality, since recognition accuracy for touch alone, following learning with both modalities present, was significant but substantially reduced relative to recognition based on vision alone or when both vision and haptic information was available. This would suggest that, when both visual and haptic information are simultaneously available in the learning of concepts that the resulting concepts are biased by visual information, with haptic information available but playing a reduced role. Finally, as was the case in Experiment 1, false recognition of the midpoint and prototype objects was lower than for the new objects closest to the category prototype.

4. The effect of partial exemplar experience on multi-modal categorization

An unexplored issue in human categorization is whether concepts can be learned when less than complete information is available. Partial information, of course, arises in most common situations - occlusion, as in ordinary perception when one object partially covers another, thereby obscuring the object, or circumstance, as when an object can be seen but not touched or touched but not seen. In the present study, we investigated the learning of concepts when an object could be viewed but not touched or the reverse. An added manipulation was the criticality of the missing information. In one condition, texture was critical to the separation of the two categories to be learned; in another, the length of the stimulus was critical. The dimensions were the length, width, and texture of the objects to be classified (the stimuli were simple elliptical shapes, with texture variations on the backside of the stimulus). When length was critical, it needed to be combined with width or texture of the same object to unambiguously classify it into category A or B. That is, length (when critical to classification) could not be used by itself; it had to be combined with either width or texture to classify the stimulus with 100% accuracy. Figure 7 shows the overall structure of the two categories in the length critical condition (not shown is the length x texture figure, which was similarly structured as length x width). Note that texture and width was not informative for classification in this condition, since the integration of these two dimensions resulted in ambiguous classification. When texture was critical, it needed to be combined with length or width for unambiguous classification (essentially the same figure but substitute texture for length). In the control condition, all three dimensions were always available for inspection, i.e., the subject was free to view and touch (the backside) of each stimulus (which varied in texture) during learning, and either length or texture was critical to classification. In all, there were 20 stimuli, 10 in each category. In the partial condition, the subject was provided partial information only on each stimulus, being able to view but not touch half the stimuli; the remaining half could be touched but not viewed. In the 'length critical' condition, the categories could be separated if length was integrated with width or texture; in the 'texture critical' condition, the categories could be separated only if texture was integrated with either length or width.

We hypothesized that the modality of the crucial dimension should have no effect in learning if all dimensions are presented simultaneously. Ernst (2007) showed that normally non-related experiences of vision and touch, namely luminance and resistance to pressure, can be integrated by showing that participants who experienced the two dimensions as being correlated had a lower threshold to discriminate stimuli than stimuli with non-correlated dimensions. Therefore, we predicted that there should be no difference in learning categorization performance between participants in the length and texture crucial dimension conditions if they have full experience with the learning stimuli. If there is a difference we would assume participants in the texture crucial dimension condition would perform worse in categorization tests across learning and transfer than subjects who studied stimuli with length as the crucial dimension due to a potential difficulty resulting from forcing participants in the texture as the crucial dimension condition to integrate across modalities.

Second, when texture is the crucial dimension there should be reliable differences in categorization performance across learning trials and transfer between subjects in the partial and complete experience conditions. The integration of the crucial dimension with its related dimensions should become more difficult, if not impossible, if the related dimensions are not simultaneously provided with the crucial dimension, as when texture is the crucial dimension, as opposed to if one of the related dimensions is provided simultaneously with the crucial dimension, as when length is the crucial dimension. As such, for participants with partial experience, those that studied categories with texture as the crucial dimension should have worse categorization performance in learning compared to participants whose crucial dimension was length.

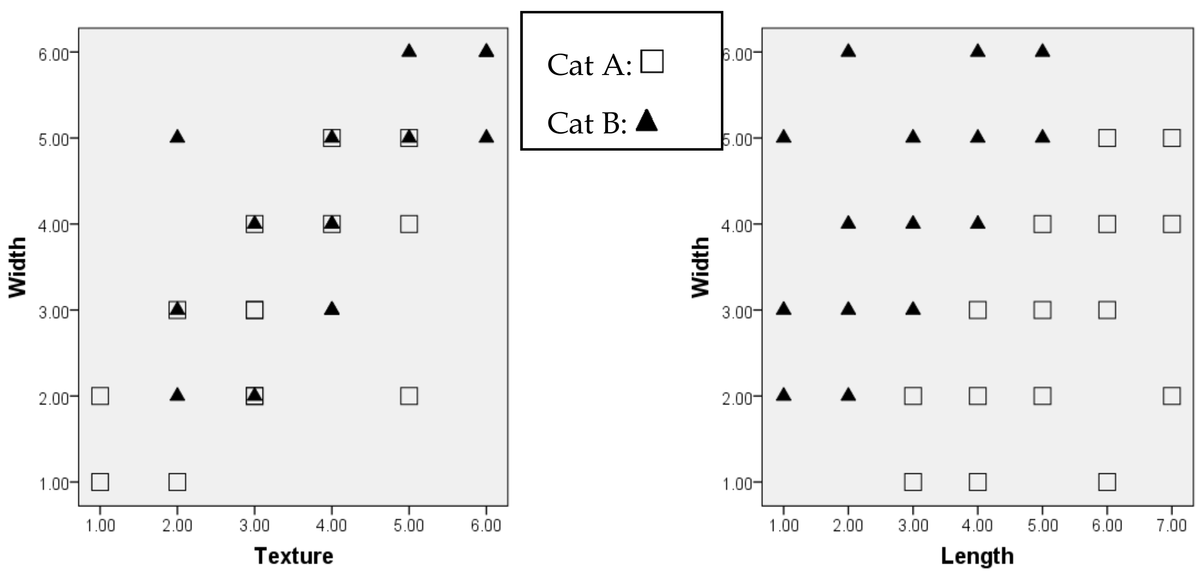

Fig. 7. Categorical structure in the length-critical condition

These two predictions would result in little difference in categorization accuracy across learning trials between participants with full experience and length as their crucial dimension, participants with partial experience and length as their crucial dimension, and participants with full experience and texture as their crucial dimension, yet all three of those groups of participants would perform very differently across learning trials from participants with partial experience and texture as their crucial dimension.

4.1 Method, procedure, and results

Subjects received 6 learning trials, the results of which are shown in Figure 8. Overall, learning was as predicted – when length was the critical dimension and learning was partial, learning was unaffected, i.e., being deprived of texture (even though texture and length could also be used to discriminate the categories) did not degrade learning, since length could always be combined with width for categorical separation. Similarly, when texture was critical, it was readily learned in the complete condition but learning was severely retarded in the partial condition. That is partial experience inhibited access to diagnostic categorical information only when texture was the crucial dimension.

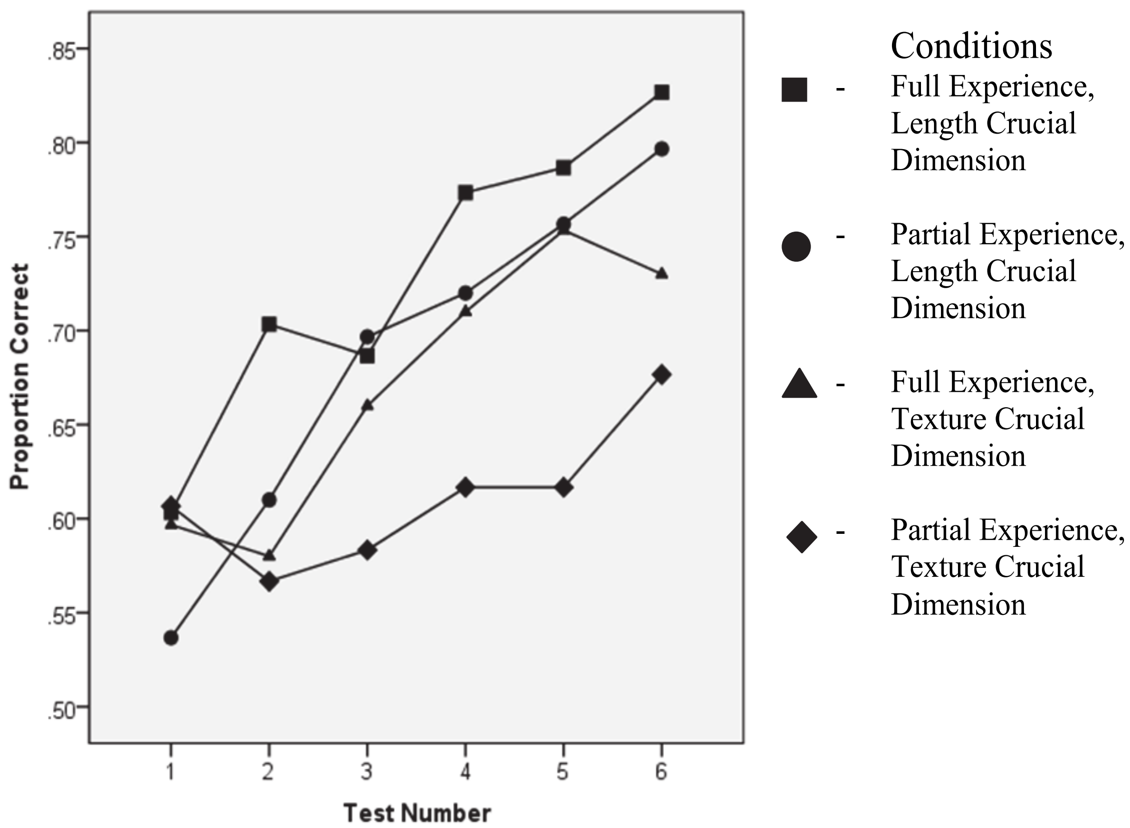

Fig. 8. Learning rate as a function of full and partial experience with length or texture as the crucial dimension.

5. Multidimensional scaling of a haptic vs. visual space

Insight into the patterning of results was further explored by multidimensional scaling of the objects. A total of six different scalings was performed, determined by haptic or visual inspection and following either no learning, random learning, or systematic learning. In each condition, the subject made similarity judgments to object pairs. We were especially interested in whether the space generated from visual judgments mirrored that when judgments were made haptically, and whether this space was further altered by prior learning. Since vision appeared to dominate haptic categories, and since more information appears to be available following visual examination, we expected that the haptic space would be structured more tightly than the visual space. This would be consistent with the hypothesis that the visual modality provides more, perhaps idiosyncratic, information than haptic exploration, and this additional information might be expected to increase stimulus discrimination and reduce overall categorical structure.

5.1 Method

Ninety Arizona State University undergraduates were drawn from the same subject pool as in previous experiments and randomly assigned to one of the six conditions. For two conditions, the similarity judgments were made either haptically or visually and followed no learning. For the remaining four conditions, learning was either systematic or random, as in Experiment 1, in the visual or haptic modality, followed by similarity judgments in the same modality as training.

Participants were either exposed to no learning or the same learning procedure used previously. They were individually tested and randomly assigned to one of the 6 conditions. Followed learning or no learning, participants were asked to make similarity judgments to the 105 possible paired-objects on a Likert-scale ranging from 1 to 9, with 1 = minimal similarity and 9 = maximal similarity. These 105 paired objects were presented randomly. For the haptic judgments, the objects were presented sequentially, with each object presented first or second about the same number of times. Ratings were self-paced but restricted to a maximum duration of 15 sec. When objects were presented visually, a similar procedure was used in which first one object was presented for inspection followed by the second object of the rating pair.

5.2 Results

The learning data mirrored that found previously, with more rapid learning for visual than haptic presentation but with terminal levels reaching nearly 100% in all learning conditions. As a consequence, the multidimensional spaces derived from similarity ratings following learning were based on comparable and near-errorless performance.

For each of the six conditions, the objects were multidimensionally scaled in dimensions 1-6. The three dimensional solutions were selected for further analysis because stress levels were low (none exceeded .05), of comparable value, and were the highest dimensionality that could be visually inspected. Three analyses were performed: (a) computation of the structural ratio (Homa, Rhodes, & Chambliss, 1979) for 15 objects as well as overall for each condition; (b) a comparison of the structural similarity among the six conditions; and (c) computation of each object to the centroid of its learning exemplars. The first measure tells us how structured each space was and whether the psychological structure mirrored objective structure. The second measure tells us whether the various scalings produced similar or different representations. The third measure assesses whether the prototype for each category was positioned away from or near the centroid of each category

The structural ratio was calculated for each of the 15 objects in a given condition by calculating the mean distance of that item to members of the same category, relative to the mean distance to objects from the other two categories. The mean of these 15 ratios for a given condition defined the mean structural ratio and represented level of conceptual structure, with smaller values indicating greater structure and values approaching 1.00 indicating a random structure. Figure 9 shows the mean structural ratio for each of the six conditions.

The structural ratios (SRs) ranged from (poorest) the space determined from visual inspection of the objects following no learning (SR = .414) to haptic inspection following systematic learning (SR = .223). In general, the structural ratios decreased with degree of learning, with the weakest structure associated with no learning (SR = .381), greatest structure with systematic learning (SR = .297), and intermediate structure with random learning (SR = .332). Overall, the haptic conceptual spaces were more structured than were the visual spaces (.301 vs. .381). To assess the similarity among the six conditions, correlations were computed among the six conditions, using as input the individual structural ratios for each object. These 15 correlations were positive and high, ranging from r = + .817 to r = + .981; the average correlation was r = +.924. A sample space – in this case, the MDS space following systematic learning in the haptic modality - is shown in Figure 10. What is clear is that the three haptic categories are clearly defined. Comparison with the original space (Figure 1) clearly reveals that the category prototype (P1, P2, P3) has become centered within each category rather than occupying the location at the extreme points of the two transformational paths.

5.3 Discussion

The results show that the haptic and visual representations of the same 3D objects were remarkably similar, suggesting that information critical to visual concepts were generally maintained following haptic inspection. As was the case in our previous studies that explored multidimensional scaling following the learning of categorical structure, the degree of structure was generally enhanced following learning (Homa et al., 1979; Zaki & Homa, 1999). As predicted, the conceptual spaces were more tightly structured following haptic examination. What seems likely is that there exists a dominant set of features critical to similarity that are comparable to the visual and haptic modality but that additional information, perhaps idiosyncratic, is more available in the visual modality. This would explain why the spaces were highly correlated and yet why the haptic space was more tightly structured.

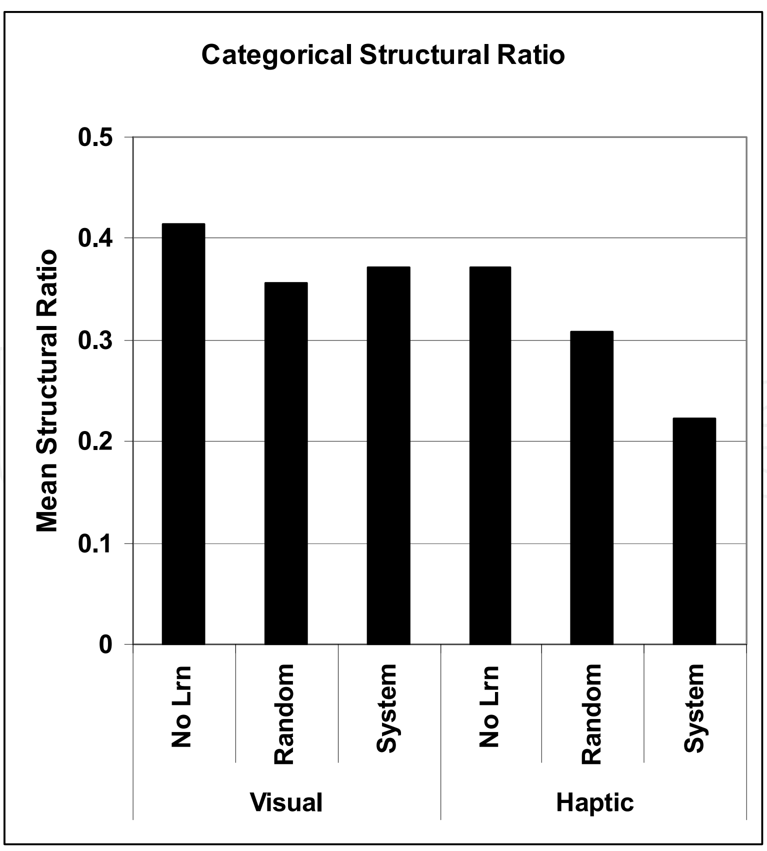

Fig. 9. Mean Structural Ratio for the six MDS solutions

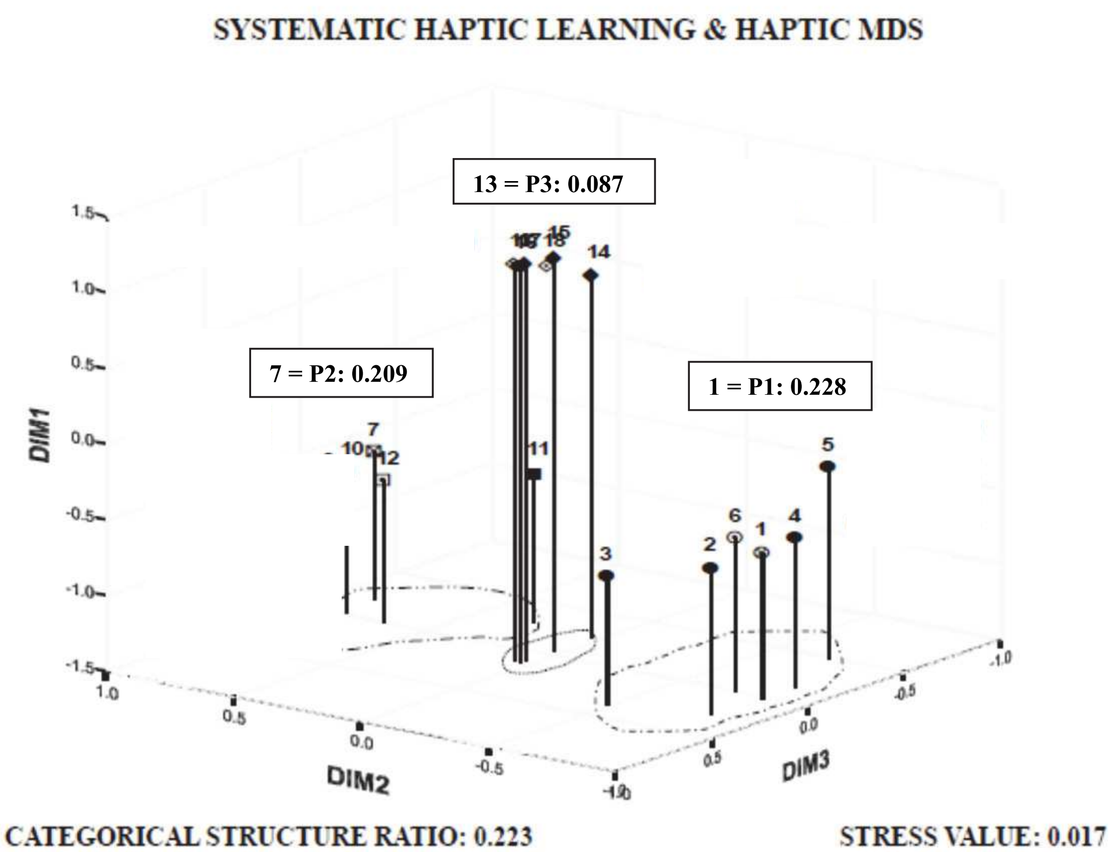

Fig. 10. Three dimensional MDS space following systematic learning in the haptic modality

6. General discussion

There exists ample evidence that vision and touch activate common neurological sites (Amedi *et al*., 2001; Ernst & Banks, 2002) and that objects experienced visually or haptically can, with fair success, be recognized in the alternate modality (Klatzky, Lederman, & Metzger, 1985; Pensky *et al*., 2008). However, almost nothing is known about the transfer of *categorical* information between these modalities. That is, can it be demonstrated that abstract categories, learned in one modality, maintain their categorical identity in an alternate modality? The answer, at least for the forms used here and considering only the visual and haptic modalities, is clearly yes.

We purposely selected fairly complex three dimensional objects that were comprised of continuous distortions from three prototypes that, informally at least, appeared to preclude simple naming of objects or even features. The major results of the three experiments that explored the learning, transfer, and retention of concepts acquired visually, haptically, or combined can be summarized: (a) Visual learning of categories, as expected, was more rapid than haptic learning, but haptic learning reached the same errorless criterion after only four study blocks; (b) When categories were learned in one modality, the classification of novel forms on a transfer test was virtually perfect, even when presented in the alternate modality; (c) The interposition of a week's delay had a statistically significant but minimal effect on classification accuracy.

The results for recognition were, however, less impressive: (a) Recognition accuracy was less accurate than classification, especially when learning occurred haptically and recognition occurred in the visual modality; (b) Transfer between the modalities was more accurate when the learning was visual rather than by touch; (c) Within-category, cross-modal conflict had no impact on learning and even appeared to enhance later recognition; and finally, (f) The psychological space for concepts acquired visually or haptically was virtually the same. We also found that presentation of the objects in a systematic, rather than random, order speeded learning and slightly improved overall transfer performance, and that the haptic space was somewhat better structured into the three categories than was the visual space.

Recognition following categorical learning was superior when the categories were formed visually and tested haptically rather than the reverse. This outcome could be explained most readily by assuming that two, distinct processes are involved in categorical recognition, an initial encoding of features relevant to the category, and a transfer of categorical information from one modality to another. A safe assumption is that the visual modality encodes more information than does the haptic modality. If the transfer from one modality to the other is not perfect, e.g., 50% of the information is transferred accurately and 50% is not, then the obtained ordering on the recognition test can be explained. That is, VV > HH = VH > HV. The multidimensional scaling of the category space, following either no learning or criterion learning, supports this interpretation, albeit indirectly. To see this, consider each object to be encoded with N-categorical features + K idiosyncratic features. Since classification transfer was accurate, with relatively few errors, we could assume that the two modalities encoded the categorical features to a similar degree. However, if the idiosyncratic features were more numerous following visual inspection, and if the idiosyncratic features are critical to later discrimination, then two outcomes would occur – recognition would be more accurate following visual training (more idiosyncratic features) and the similarity judgments, used to map the categorical spaces, would be more distinctive when objects were compared visually. Phillips et al. (2009) found that increasing object complexity influenced haptic judgments more than visual judgments, an outcome that would be consistent with the view suggested here. An alternative test would require that features more amenable to haptic than visual processing, such as texture and weight differences, be incorporated into a categorical paradigm. Under these circumstances, haptic recognition might improve overall and produce an MDS space that represented within-category objects as slightly less similar to each other.

Four other results are notable. First, systematic training had a small but consistently positive effect both in learning and later recognition, a result that replicates Zaki and Homa's (1999) study using two dimensional categorical stimuli. Second, the placement of the category prototypes in the multidimensionally-scaled space failed to preserve the prototype as an endpoint object of its category. Rather, the category prototype, especially following a learning phase, was found to gravitate more toward the center of its psychological category. Third, cross-modal conflict had a negligible effect in either learning or later transfer. In fact, this conflict seemed to enhance later recognition. Our impression is that most subjects failed to notice a conflict when the object explored visually and haptically were different, presumably because the objects were not namable, lacked dramatically different features, and belonged to the same category. It is less clear whether the subject integrated the slightly disparate sensations from the two different stimuli on each trial, formed a composite memory trace that included both visual and haptic features, or formed bi-modal concepts for each category. The last outcome seems least likely, since the learning of multiple categories should produce a slowing of category learning, an outcome not obtained. Regardless, additional research with categories composed of more distinctive features, e.g., texture differences, might permit separation of these competing explanations. Finally, the category prototype and midpoint objects were falsely recognized less often than other new objects. This occurred even though the midpoint objects were flanked by two similar training objects as were the new objects; the category prototypes similarly had two training objects that were similar as well. What seems likely is that exemplar similarity (e.g., Nosofsky, 1988) alone was not the sole determinate of recognition. Rather, categorical influences likely mitigated false recognition, since, for the midpoint objects, the two flanking training objects belonged to different prototypes. Why the category prototypes were not falsely recognized more often (or at least as often as the new objects) is less clear. However, the location of the prototypes, as an object at the vertex of two divergent paths, may have insulated the category prototype from false recognition because of extra-experimental knowledge, e.g., the subject might sense that the prototype is a generative pattern, not an old one. Regardless, there exists prior evidence that the category prototype may be treated as a novel ideal point rather than a familiar one based on object similarity alone (Homa *et al*., 1993; Homa *et al*., 2001).

Future research into multi-modal concepts, including situations where less than full stimulus information is available, is critical to a comprehensive theory of concepts. Creative paradigms that involve modalities other than visual and haptic processing is obviously needed, as are the criteria needed to address what is perhaps the most fundamental question of all in this domain – what evidence would suggest that our concepts become modality-free or modality-preserving?

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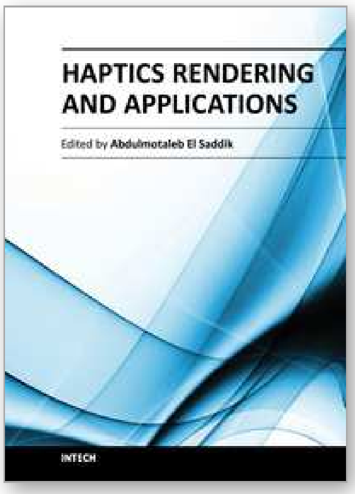

Haptics Rendering and Applications
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There has been significant progress in haptic technologies but the incorporation of haptics into virtual environments is still in its infancy. A wide range of the new society's human activities including communication, education, art, entertainment, commerce and science would forever change if we learned how to capture, manipulate and reproduce haptic sensory stimuli that are nearly indistinguishable from reality. For the field to move forward, many commercial and technological barriers need to be overcome. By rendering how objects feel through haptic technology, we communicate information that might reflect a desire to speak a physically-based language that has never been explored before. Due to constant improvement in haptics technology and increasing levels of research into and development of haptics-related algorithms, protocols and devices, there is a belief that haptics technology has a promising future.