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The Role of Learning Modality upon Long-Term Spatial Memory

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THE ROLE OF LEARNING MODALITY UPON LONG-TERM SPATIAL MEMORY

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DALE A. HIRSCH

ABSTRACT

Spatial cognition often requires the contemplation of multiple discrete layouts. Determining the relative direction of objects between distinct layouts comes with a cost to accuracy when compared to determining the relative direction among objects from within the same layout. The decrease in accuracy that results from comparing discrete layouts is called integration cost (Yamamoto & Shelton, 2008). Yamamoto (2007) found that the cost of integration between two layouts learned through the same modality is equivalent to the cost of integrating between two layouts learned through different modalities (i.e., vision and proprioception). Yamamoto's findings suggest that modulating the learning modalities of layouts does not affect the cost of integrating those layouts. According to the amodal theory of spatial cognition, spatial representations are not dependent upon learning modality. Yamamoto's findings are consistent with the amodal theory. However, it is important to know whether this equivalence is unique to the relationship between vision and proprioception, the modalities used by Yamamoto, or whether it is observable between other modalities as well. The proposed experiment is therefore designed to investigate the relationship between vision and haptics as it relates to integration cost. The hypothesis is that integration cost will occur equally within and between modalities. If this is the case, then it will provide further support for the theory of amodal spatial representation. Such a result would show that the spatial information used to integrate spatial representations in long-term memory is not dependent upon encoding modality.

TABLE OF CONTENTS

	Page
ABSTRACT.....	iii
LIST OF FIGURES.....	v
CHAPTERS	
I. INTRODUCTION.....	1
II. METHOD.....	7
III. RESULTS.....	13
IV. DISCUSSION.....	15
REFERENCES.....	21

LIST OF FIGURES

Figure	Page
1. Layouts and Learning Conditions.....	8
2. JRD Trial Types.....	9
3. Integration Cost.....	14

CHAPTER I

INTRODUCTION

The way in which spatial representations are informed might appear to be fairly straightforward. The senses detect environmental cues and translate them into electro-chemical signals to be sent to the brain for perception and encoding. However, the nature of spatial representation is debated when it comes to the relationship between the spatial representation and the sensory modality through which that representation was learned. There are two major theories on this topic: multimodal representation and amodal representation. The multimodal representation theory suggests that spatial representations are bound to the modality of initial encoding. In other words, each sensory modality creates its own representation of a space. On the other hand, the amodal theory posits that, although the senses are responsible for gathering spatial information, the senses do not play a role in the representations themselves. Beyond perception, spatial information becomes independent of the senses and exists in its own spatial realm. These theories are discussed in more detail below.

The multimodal theory is based on the idea that learning modalities are encoding

modalities. If a spatial layout is perceived through a particular sense, the multimodal theory suggests that the mental representation of that layout will also be encoded through that sense. The final representation is, therefore, modal in nature. The multimodal theory also claims that for any single space, multiple sensory-specific representations are formed. One's bedroom for example would be spatially represented multiple times within the mind, once for each sense that has spatially perceived the room. Visual perception of the room would result in a visual representation of the room. While, proprioceptively experiencing the room would result in a proprioceptive representation. Although visual and proprioceptive experiences of one's bedroom may be concurrent, the multimodal theory claims that these divergent sensory experiences form discrete sensory-specific representations. Support for the multimodal theory has been found in experiments that require participants to demonstrate spatial knowledge using a sensory specific reconstruction task (Yamamoto, 2007).

Yamamoto (2007) had participants learn a single spatial layout from two perspectives using two different modalities: One perspective was learned visually and the other was learned proprioceptively. Visual learning was done from a stationary position. Proprioceptive learning required participants to be blindfolded and led to several object positions by the experimenter. Participants were led forward, left, or right to each consecutive object location while continually maintaining the initial orientation. After learning the layout, participants were instructed to recreate the layout using one of the two senses used during the learning phase. Results showed that the orientations of participant reconstructions were dependent upon which modality was used to reconstruct the layout. When reconstruction was done visually, the perspective taken during visual

learning was displayed by the visual reconstruction. Likewise, proprioceptive reconstructions adopted the perspective from which proprioceptive learning was carried out. These results suggest that a spatial layout learned from two perspectives, each through a different modality, is represented by two sensory-specific representations within the mind. As stated above, multiple sensory-specific representations of the same layout constitute the definition of the multimodal theory. However, there is also evidence in favor of the amodal theory.

Despite the fact that a layout may be learned through one or more modalities, only a single mental representation is created for any one real-world layout at any one time according to the amodal theory. Using the bedroom example again, the amodal theory claims that multi-sensory (e.g., visual and proprioceptive) exposure to one's bedroom will result in a single unified representation that is neither visual nor proprioceptive in nature. Therefore, seeing and feeling one's room will result a singular representation of the space despite multiple sensory inputs. Furthermore, the single representation is not sensory specific even in instances of single modal learning. The amodal theory claims that spatial representations are stripped of sensory information and are therefore encoded in an amodal manner. The amodal theory also requires that spatial representations be functionally equivalent. If all representations are stored in the same amodal fashion, then it is reasonable to assume that those representations should behave similarly. If each modality creates a functionally equivalent representation, as suggested by the multimodal theory, then a sensory-specific representation for each modality is redundant. A single, unified, amodal representation of a layout is therefore more efficient than multiple modality-specific representations of the same space. Evidence for amodal representation can be found when participants are required to display their spatial knowledge in an

abstract or non-sensory specific way (e.g., judgements of relative direction).

Yamamoto (2007) found equivalence of integration cost between two distinct layouts. Yamamoto had participants learn a 10-object layout in two 5-object phases. Participants learned the first five objects to criterion either visually or proprioceptively, then learned the second five objects to criterion either visually or proprioceptively. Four learning conditions resulted. They were vision-vision, vision-proprioception, proprioception-vision, and proprioception-proprioception. The main finding from this experiment was that regardless of the learning type there was equivalent integration cost between the two 5-object sub-layouts. The results showed that the cost of integration between layouts learned through the same modality was equivalent to the cost of integration between layouts learned through different modalities. The integration of two visually learned layouts had the same integration cost as two layouts learned through vision and proprioception, respectively. Yamamoto interpreted this as evidence for amodal representation. However, it is unclear if this relationship is unique to vision and proprioception or if other modalities share this functional equivalence. This experiment is therefore designed to investigate whether Yamamoto's findings can be replicated using different modalities. This experiment will use haptic learning instead of proprioceptive learning in order to investigate the integration cost within and between vision and haptics. Haptics is the next logical step in this line of research because of its similarity to proprioception. Both haptic and proprioceptive senses rely upon peripheral body movement to detect direction and distance. The similarity of haptics to proprioception allows for a fairly seamless recreation of the Yamamoto experiment while using a new modality. The similarity also allows for a strong hypothesis. That is, the integration costs found between and within haptics and vision will likely mimic the integration costs

between and with proprioception and vision. Several previous experiments have explored the relation between vision and haptics (e.g., Feron, Gentaz, & Steri, 2006; Giudice, Klatzky, Loomis, 2009; Newell, Woods, Mernagh, & Bühlhoff, 2005), but they did not investigate the integration cost within and between these modalities. This experiment, however, will focus upon the costs of integrating long-term spatial representations of layouts learned through vision and haptics.

A common factor when exploring spatial cognition is gender. A multitude of previous studies have shown an effect of gender, favoring males, upon spatial reasoning tasks. This is especially true for tasks that require mental rotation and perspective taking (e.g., judgments of relative direction) (see Maeda & Yoon, 2012, for review). While prevalent in adults, the gender gap for spatial ability is also present in children (Stumpf & Eliot, 1995; Tzuriel & Egozi, 2010). Some, however, have argued that the gender gap in spatial ability is due more to nurture than nature. Hoffman, Gneezy and List (2011) showed the existence of a significant gender gap for spatial ability in several patriarchal villages of India while nearby matriarchal villages showed no such gap. The authors concluded that society and not gender was the dominant factor in spatial ability. Regardless, gender will be included as a factor to investigate any possible effect. If an effect of gender is found, it is likely to favor the male participants.

In addition to expanding the knowledge of integration cost by replacing proprioceptive learning with haptic learning this experiment also provides a methodological advantage over Yamamoto (2007). Yamamoto's proprioceptive learning phase involves moving blindfolded participants around the room to different object locations. While the participants continue to face the same direction throughout the learning phase, their location continued to change. With their location in the layout

constantly changing, their position relative to each object also changed. Visual learning, however, occurred from a single stationary position. It is not clear what effect, if any, this variation of location has upon long-term spatial representations. However, replacing proprioceptive learning with haptic learning will eliminate this issue. Haptic learning, as well as visual learning, will occur from a single location (details will be shown in Chapter 2). A single reference position will be commonly available during visual and haptic learning.

CHAPTER II

METHOD

Participants

Thirty-two individuals from the Cleveland State University community participated in this study. Participants were 16 males and 16 females with normal or corrected-to-normal vision. All participants received compensation for their time either monetarily or with course credit.

Materials

Learning materials included two spatial layouts. Each layout was comprised of 10 distinct objects, which were divided into two five-object sub-layouts. Any one participant was only exposed to a single 10-object layout. Each object had a unique combination of color, shape, and name. Objects occupied pizza boards approximately 40.5 centimeters in diameter (see Figure 1A). Learning took place in a circular area designated by an opaque curtain approximately three meters in diameter. Participants sat at a round table approximately 40 cm in diameter at the center of the circular area. All participants wore a blindfold and hearing protection to damper ambient sensory stimuli.

Participants were required to wear a cotton glove while touching the objects in order to prevent injury. The experimenter carried a stopwatch in order to regulate the exposure time of each sub-layout.

Design

This experiment utilized a 4x4x2 design: learning condition (4) x trial type (4) x gender (2). Learning condition and gender are between-subject factors while trial type is a within-subject factor. The four learning conditions are as follows: vision-vision, vision-haptic, haptic-vision, and haptic-haptic (see Figure 1B). In the vision-vision condition, for example, participants are visually presented the first sub-layout followed by a visual presentation of the second sub-layout (see Figure 1A).

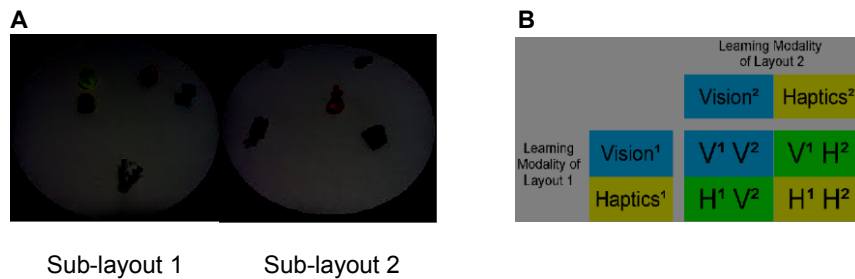


Figure 1. Example sub-layouts used for the learning phase (A). There are four learning conditions V-V, V-H, H-V, and H-H (B).

Gender was also included in the analysis to explore any possible effect for gender. However, because gender did not have a significant effect in the current experiment, gender was collapsed for the remaining analysis.

The single within-subject factor, trial type, consists of four different types of judgments of relative direction (JRD). After learning the layout, participants will perform JRDs of object locations in the layout by using their long-term memories of the learned layout. The JRD requires participants to imagine three of the 10 objects in the layout.

First is the base object that the participant is to imagine being located at. Second is the orienting object that the participant is to imagine facing from the first object. The final object is the target, which the participant is to indicate the direction of. The four trial types in the JRD task are denoted as AA-A, AA-B, AB-A, and AB-B. The A's and B's represent within-sub-layout objects and between-sub-layout objects respectively. A trial type of AA-A consists of three objects from the same five-object sub-layout. An AA-B trial consists of two objects from a single sub-layout, which defines the imagined heading, and one object from the other sub-layout that will be the target. AB-A trials require participants to orient across sub-layouts and then target an object from the base sub-layout. Whereas, a trial type of AB-B requires an orientation across sub-layouts and then a targeting of an object from the second sub-layout. A's and B's are not designators of sub-layout, but merely indicators of the relationship among the objects of a JRD trial (Figure 2).

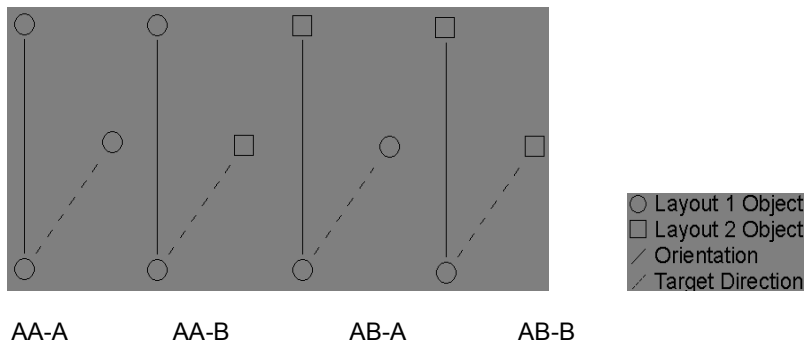


Figure 2. JRD trial types. An AA-A trial contains three objects from the same sub-layout. An AA-B trial uses two objects oriented within the same sub-layout and targets an object in the other sub-layout. An AB-A trial is oriented between sub-layouts and targets an object from the starting sub-layout. An AB-B trial is oriented across sub-layouts and targets an object from the second sub-layout.

All four learning conditions receive counterbalancing for learning order (sub-

layout A or B presented first), and 10-object layout (1 or 2). The dependent variable of the JRD trials is absolute angular error. That is, the absolute angular distance between the direction of the actual target and the direction indicated by the participant.

Procedure

Participants first completed a consent form followed by a short demographic questionnaire. The questionnaire asked participants to indicate their gender and handedness. The experimenter then described the learning phase to the participants. They are to memorize a 10-object layout in two five-object parts. Participants were explicitly told to learn the two five-object sub-layouts as a 10-object whole. The experimenter then introduced the participant to the 10 objects that constituted their layout. Each object was presented one at a time in random order. The experimenter named each object and handed it to the participant. The participant was allowed to see, feel, and hear the name of each object. At no point, however, did the objects resemble the experimental layout. Participants were not be exposed to the experimental layout until the learning phase began. Participants were then asked to don the blindfold, hearing protectors, and glove. The glove was worn on the dominate hand as indicated on the demographic form. The experimenter then led the participant to the learning area, which was located in another area. During the relocation, participants were disoriented by following an indirect path to the learning area. This disorientation was to eliminate any spatial references that may be lingering in the participant's mind. It was important that all participants assume the same reference orientation as dictated by the experimental design. The participants were seated at a table within the learning area. The first sub-layout was set before the participant. Visual learners were then asked to remove their blindfolds and observe the sub-layout. Haptic learners remained blindfolded and explored the sub-

layout manually with their gloved hand. Exposure time was 30 seconds for both visually and haptically learned sub-layouts. Following the initial exposure, all participants wore the blindfold and indicated the name and location of each object by pointing. No touching of the objects was allowed during pointing. After pointing to, and naming, each object, participants were shown the layout again. Any errors in locating or naming the objects was self-corrected by the participants during the subsequent study period. This study-test sequence was repeated until participants learned the sub-layout to criterion. The learning criterion was met when participants were able to accurately and fluently name and locate every object in the sub-layout on two consecutive attempts. Upon learning the first sub-layout to criterion, the participants moved on to the second sub-layout. Participants then learned the second sub-layout to criterion. The learning phase was then concluded.

Participants then followed the experimenter back to the original area for testing. Again, participants were disoriented, this time to remove the relative location of the layout from their minds. The only orientation participants should have had to the layout was the orientation observed during the learning phase. Testing took place on a computer using a custom program. Participants first received instruction on the general testing procedure. Participants then learned, and practiced, the JRD procedure by using prominent campus locations. Participants were to imagine being at building A while facing building B. They were then to indicate the relative direction of building C. Participants conducted eight of these practice trials in order to master the JRD concept. Any errors during the practice trials received immediate correction and explanation by the experimenter. After successful completion of the practice session, participants moved on to a pre-experimental session of eight additional trials that utilized actual objects from

the learning phase. The pre-experimental session allowed participants to manipulate the newly learned layouts before the actual test trials begin. Pre-experimental trials were intended to ensure that the participants' representations of the layout had been fully activated, and to prevent any possible warm-up period from contaminating the actual trial data. Data collected from the practice and pre-experimental trial sessions were not analyzed. The testing phase consisted of two blocks of 64 trials. Each participant completed 128 JRDs.

Once the JRDs were finished, participants constructed a map of the learned layout. Map drawing also occurred on the computer. The screen displayed a list of 10 object names and a circle. Participants were required to select each name and place it within the circle. Object placement was to be relative to one another in an attempt to recreate the actual layout. The map drawing is useful for assessing the accuracy of participants' mental representations of the layout. Participants who display higher absolute angular error during the JRD trials were expected to create more distorted recreations of the layout during map drawing. The experimenter then thanked the participant for their time and cooperation and allowed for any questions that they might have. The experiment was then be concluded.

CHAPTER III

RESULTS

The data were analyzed using a 4x4x2 mixed analysis of variance (ANOVA). Learning condition (vision-vision, vision-haptic, haptic-vision, and haptic-haptic) and gender (men and women) are between-participant factors. Trial type (AA-A, AA-B, AB-A, and AB-B) is a within-participant factor. Seven participant's data were excluded from the analysis due to excessive error (i.e., average absolute angular error ≥ 90). Furthermore, the correlation between reaction time and accuracy was calculated ($r = -.02$) which indicates a lack of speed-accuracy tradeoff. Outliers, defined as the grand mean $\pm 3SD$, were non-existent due to large variance in the data ($M = 63.32$, $SD = 18.23$). In addition, the data were analyzed using mean reaction time as the dependent variable. This analysis resulted in a similar pattern to that found for absolute error. Another attempt to clarify the pattern found below involved replacing each individual trial having an absolute error at or above 90 degrees with the mean error for that trial type for each participant. This analysis yielded a smaller grand mean error ($M = 47.42$, $SD = 13.15$), however the pattern was unaltered and a violation for equality of variance occurred.

Therefore, the original, unaltered and violation free data were used for the final analysis.

The results of the JRD can be seen in Figure 3.

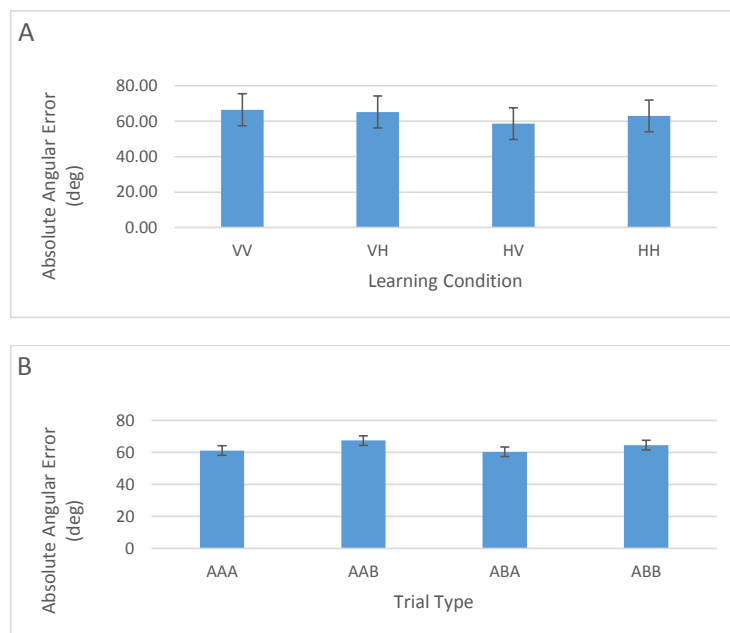


Figure 3. Absolute angular error for JRDs for (A) learning condition and (B) trial type. Error bars represent ± 1 SEM.

A significant main effect was found for trial type, $F(3, 72) = 5.092, p = 0.005, \eta_p^2 = 0.175$. No significant effect was found for learning condition, $F(3, 72) = 0.303, p = 0.823, \eta_p^2 = 0.037$. Nor was there a significant interaction between trial type and learning condition, $F(9, 72) = 1.19, p = 0.324, \eta_p^2 = 0.129$. Planned comparisons of trial type revealed AA-A and AB-A trials were more accurate than AA-B. The comparison statistics for trial type are: AB-A vs. AA-B, $F(1, 31) = 16.24, p < 0.001, \eta_p^2 = 0.404$; AA-A vs. AA-B, $F(1, 31) = 11.07, p = 0.003, \eta_p^2 = 0.316$. No other comparisons reached significance.

CHAPTER IV

DISCUSSION

The obtained results support the hypothesis that the cost of integrating layouts is uniform within and across modalities. However, the pattern of these results was unexpected. An increase in error was found between AA-A trials and AA-B trials. This increase in error is to be expected because of the integration of sub-layouts required by the AA-B trials that is not required for the AA-A trials. The extra cognitive load of an AA-B trial explains the higher average angular error found in these trials. However, AB-A trials, which also require integration, had the lowest average angular error of any trial type. The final trial type, AB-B, which did have a higher average error than did AB-A trials was not significantly larger than the AA-A trials that require no integration at all. The relatively low angular error for AB-A trials and the subsequent irregular pattern for trial type is difficult to explain.

One explanation for the irregular pattern of data may be the relative difficulty of the task. Yamamoto 2007 found a grand mean of approximately 40° for JRDs on a similar task. The participants in this experiment, however, showed a grand mean of 62.31°. This

drastic increase in error may be due to the difference in scale between the two experiments. Yamamoto used a room-sized layout nearly three meters in diameter while the current experiment utilized a tabletop-sized layout approximately 40 centimeters in diameter. If, for example, a participant remembered an object 10 centimeters left of its actual position, that object's relative location in Yamamoto's room-sized layout would be fairly unchanged. However, that same 10 centimeter error in the current experiment would yield a much larger change relative to the other objects in the layout. It is reasonable to suppose that scale may have played a role in the differential results of these two similar experiments.

Another possible explanation for the difference in error between Yamamoto's room-sized experiment and the current study is general spatial ability. By only examining the data for the more accurate half of the participants, those participants with a grand mean less than 65°, a pattern more similar to that of Yamamoto emerges. Trial types AA-A, AA-B, AB-A, and ABB for the more accurate half of participants showed means of 41.81, 51.61, 46.43, and 49.08 degrees respectively. It seems that accuracy may affect the pattern of trial types. It is possible that the different patterns found for the two experiments are the result of sampling two different populations with different spatial abilities.

Yamamoto 2007, whose research this experiment is based, found AA-A trials to have significantly less error than all other trial types. More importantly, to spatial representation theory, Yamamoto also found no effect for learning condition. The current experiment also found no effect for learning condition. The same cost resulted from integrating two visually learned layouts as resulted from integrating a visually learned layout and a haptically learned layout. The learning modality of a spatial layout did not

affect the cost associated with integrating it with another layout. The functional equivalence of spatial integration may be explained in one of three ways.

First, the representations are indeed amodal. In other words, after learning a layout, it is encoded in an amodal fashion. Upon retrieval, the learning modality of the spatial layout is no longer relevant. Amodality explains the functional equivalence of spatial representations learned through different modalities. Two amodal representations will exhibit functional equivalence because they do not have sensory-specific incompatibilities. Learning modality is simply a way to receive information. Learning modalities are not necessarily encoding modalities when it comes to spatial information.

The second possibility is that learning modalities are also encoding modalities in that the final representation is modal in nature. However, for this to be the case there must be an explanation for the functional equivalence in the findings. That is, despite their distinct differences, modalities display very similar behavior on JRD tasks. If the modalities are sufficiently distinct to warrant their own spatial representations, it is redundant for those spatial representations to be so similar. However, it is possible that the sensory systems, having evolved separately, developed their own spatial representations. If so, such spatial representations would only be purposeful if they were accurate. In such a case, functional equivalence may be accounted for by the relative precision of multiple sensory-specific representations.

The third explanation for the functional equivalence of spatial integration is the possible interaction or combination of the amodal and multimodal theories. A mixed-modal theory can reconcile functional equivalence by suggesting that representations may be stored in a sensory specific manner, as suggested by the multimodal theory, but while in working memory the representations may take on an amodal form. Perhaps working

memory is only concerned with the amodal components of the representation and therefore ignores the sensory specific information that is available. If working memory only manipulates the amodal components of an otherwise sensory specific representation, functional equivalence between representations is likely to occur regardless of learning modality. While philosophically reasonable, this explanation allows for innumerable combinations and derivations. Such an adaptive theory is of little predictive use to the scientific community. However, previous studies that have claimed evidence for the amodal or multimodal theories have often also provided evidence for mixed-modal representation. Evidence for the amodal and multi-modal theories often rely on task demands. That is, if the task is amodal (e.g., JRDs) and not sensory-specific in nature the data do not show an effect for learning modality. However, when the task is sensory-specific, as in a reconstruction task, an effect for learning condition is found.

Guidice, Betty, and Loomis (2011) found functional equivalence for visual and haptic map reading. They had participants learn routes from maps either visually or haptically. Participants then demonstrated their knowledge of the routes with a blind-walking task. The authors found functionally equivalent performance for the blind-walking task regardless of whether the routes were learned visually or haptically. Such results may be predicted by a mixed-modal representation. Because the task, blind-walking, was unrelated to either learning modality the results demonstrated functional equivalence between vision and haptics. If, however, the task demand was sensory-specific, that is visual or haptic in nature, a mixed-modal theory would predict an effect for learning modality.

Newell, Woods, Mernagh, and Bülthoff (2005) found an effect for learning condition in their study of scene recognition. The participants first learned a tabletop

sized layout either visually or haptically. Then the experimenter switched the locations of two objects from the layout. The participant was then required to determine which of the two objects had been switched using either their vision or their haptic sense. As a mixed-modal model of spatial representation would predict, the sensory-specific task in Newell et al. (2005) resulted in a significant effect for learning condition. Those participants whose determination was made through the same sense as was used to learn the layout, were significantly more accurate than those participants whose study-test sequence was cross-modal. In other words, when participants were asked to determine which objects had been switched, those participants with a unimodal study-test sequence were better at choosing the correct objects than were participants in the cross-modal condition.

While the multimodal and mixed-modal theories may be possible, the amodal theory still provides the cleanest and most parsimonious model of human spatial representations in long-term memory. Amodal representation may stand out theoretically, however, the actual form and activity of spatial representation in human long-term memory is less clear. This issue requires further investigation.

This experiment was designed to furthering the knowledge of integration cost. The hypothesis was supported by the data, integration cost does appear to operate outside of the influence of learning modality. However, given the unusual pattern found in this experiment, further investigation of integration cost is still needed. Even though this experiment's results support of the hypothesis, many other sensory relationships are still unknown when it comes to the amodality of integration cost. Haptics and proprioception are very similar as senses go. They both rely upon afferent and efferent signals to and from the peripheral nervous system to direct and detect body movements. Therefore, their seemingly similar relationship to vision may not be that surprising. Further tests of

integration cost involving audition would be very interesting. In order for the amodal theory to stand, audition must also be abstracted into a purely amodal spatial representation. If audition exhibits different behavior than has been found with other senses then the amodal theory will fail.

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