RUNNING HEAD: Cue Interaction in Reorientation

Effect of Room Size on Geometry and Features Cue Preference during Reorientation: Modulating Encoding Strength or Cue Weighting

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Abstract

Three experiments investigated how the room size affects preferential use of geometric and non-geometric cues during reorientation inside a room. We hypothesized that room size may affect preferential use of geometric and non-geometric cues by affecting the encoding of the cues (the encoding hypothesis), the retrieval of the cues (the retrieval hypothesis), or both the encoding and retrieval of the cues (the encoding-plus-retrieval hypothesis). In immersive virtual rectangular rooms, participants learned objects' locations with respect to geometric (room shape) and non-geometric cues (features on walls or isolated objects). During the test, participants localized objects with the geometric cue only, non-geometric cues only, or both. The two cues were placed at the original locations or displaced relative to each other (conflicting cues) when both were presented at testing. We manipulated the room size between participants within each experiment. The results showed that the room size affected cue preference using conflicting cues but did not affect response accuracy using single cues at testing. These results support the retrieval hypothesis. The results were discussed in terms of the effects of cue salience and stability on cue interaction in reorientation.

Keywords: Reorientation, room size effect, geometry, feature, cue interaction.

Introduction

When navigators lose track of their orientation, they should reorient themselves using multiple cues in the environment. Those cues include geometric cues and non-geometric features. Geometric cues refer to distance to or geometric relationships among extended surfaces. Non-geometric features include 2D patterns and isolated objects (Lee & Spelke, 2010). Plenty of studies have investigated the interaction between geometric and featural cues during reorientation (for reviews, see Cheng & Newcombe, 2005; Twyman & Newcombe, 2010; Vallortigara, 2009). One of the most interesting phenomena is that the use of geometry and features is modulated by the size of the environment.

Previous studies showed that young children could not use features to reorient in small rooms (4 by 6 feet, Hermer & Spelke, 1994, 1996) but could do so in large rooms (8 by 12 feet, Learmonth, Nadel, & Newcombe, 2002). Similarly, increased use of featural cues in larger enclosures was also found in animal reorientation (fish: Sovrano, Bisazzaa, & Vallortigara, 2005; rats: Maes, Fontanari, & Regolin, 2009). More interestingly, when geometry and features were placed in conflict, human adults, chicks, and fish were more likely to follow the geometric cue in a small room than in a large room, and were more likely to follow the featural cue in a large room than in a small room (Ratliff & Newcombe, 2008; Sovrano & Vallortigara, 2006; Sovrano, Bisazzaa, & Vallortigara, 2007; but see Lambinet, Wilzeck & Kelly, 2014). In sum, all the previous studies showing a room size effect on the use of features and geometry suggested that the role of geometry is weakened, and the role of features is strengthened as the environmental size increases.

However, the reason for the room size effect on the relative use of geometry and features in reorientation remains unclear. Newcombe and Huttenlocher (2006) proposed that geometry and features are combined in a Bayesian fashion with their weights determined by cue properties such as salience and stability. Therefore, the room size effect may be attributed to different salience and stability of geometry and features in large and small rooms. This theory did not specify the memory stage in which cue salience/stability affects cue preference. The room size effect could be attributed to the effect of cue salience/stability on cue preference in encoding of orientations, retrieval of orientations, or both.

Miller (2009) suggested that the room size affects the relative use of geometry and features by affecting the salience of the cues during encoding. In an associative model developed by Miller and Shettleworth (2007, 2008), the relative use of cues is determined by the associative strength between each cue and the target, and the increment in associative strength is positively related to the salience of the cue. Miller (2009) speculated that because the relative salience of features increases with room size, the relative use of features increases with room size. He assigned a greater salience value to the featural cue in a large enclosure than in a small enclosure, and a greater salience value to the geometric cue in a small enclosure than in a large enclosure, and successfully simulated the room size effect found in previous studies (Chiandetti et al., 2007; Learmonth et al., 2002; Sovrano & Vallortigara, 2006; Vallortigara et al., 2005).

The salience of features may relate to the sizes of features. Gouteux and colleagues (2001) kept the room size constant and changed the size of the featural cues. They found that monkeys were more likely to use featural cues when the cues were larger, and therefore, more salient. In some cases, features in larger enclosures are naturally larger than those in small enclosures. For example, if the featural cue is a colored wall, as the room becomes larger, the colored wall also becomes larger. This may explain the room size effect that features are more likely to be used in larger rooms because features are more salient in larger rooms.

However, when participants were restricted at the center of the room (Ratliff & Newcombe, 2008), larger features may not always lead to a larger perceived salience. As the enclosure becomes larger, the distance between the colored wall and the navigator also increases. As a result, the colored wall occupies the same retinal area in a small room as in a large room, although its absolute size is bigger in a larger room. Thus, the salience of the features may remain the same. Moreover, for an isolated object, although its absolute size remains the same, it occupies a smaller retinal area because it is farther from the observer in a larger room. Thus, the salience of the features may decrease as opposed to Miller's assumption (Miller, 2009). Therefore, feature size may not explain the room size effect found when participants were restricted at the center of the room (Ratliff & Newcombe, 2008).

Sovrano and Vallortigara (2006) speculated that a negative relationship between room size and the salience of geometric cues might have contributed to the room size effect. They suggested that when keeping a certain distance from a corner, free-moving navigators can see a larger portion of the room in a small room than in a large room, allowing them to more easily infer the geometric relationships among different parts in a smaller room. This speculation also predicts that there is no room size effect if participants stay only at the center of the room. For them, the salience of the geometric cue should not differ in the small and large rooms. This speculation is supported by Learmonth and colleagues (2008). In their finding, young children could use a colored wall to reorient in a large room when they could freely move in the enclosure but could not use the colored wall when their movement was restricted. However, this speculation still cannot explain the room size effect reported by Ratliff and Newcombe (2008), because in their study, the human adult participants were only standing at the center of the room.

The distance of cues may have contributed to the room size effect by affecting cue stability. Sovrano and colleagues (2005) speculated that navigators only use features beyond a certain distance as an orientation cue. Nadel and Hupbach (2006) suggested that a proximal landmark is not preferred as an orientation cue because its orientation with respect to the observer changes rapidly when the observer moves, whereas a distal landmark is a better orientation cue because its orientation remains relatively constant when the observer moves. This assumption was supported by neuroscience studies showing that head direction cells mostly followed distal landmarks when distal and proximal landmarks were in conflict (Yoganarasimha, Yu, & Knierim, 2006). On the other hand, the geometric shape of a room could indicate orientations with its own frame of reference (e.g. the principal axis). Its immunity to the observers' movements is not affected by room size. In sum, features are more likely to be used in larger rooms because they are more distal and therefore less vulnerable to observers' movements.

In the current study, we are particularly interested in at which memory stage(s) the room size effect takes place. We hypothesized that the room size may affect using cues in encoding participants' orientation (encoding hypothesis), in retrieving participants' orientation (retrieval hypothesis), or both (encoding-plus-retrieval hypothesis). Figure 1 describes these three hypotheses to explain the room size effect reported in the previous study (e.g., Ratliff &Newcombe, 2008). In the current study, we use *encoding strength* to refer to the degree of learning cues in encoding participants' orientation. We use *cue weighting* to refer to the process of weighting the estimated orientations based on different cues.

To test these three hypotheses, first, we examined whether the room size modulated the relative *encoding strength* of the room shape and the features. *Encoding strength* can be measured as the *response accuracy* in reorientation when only a single cue is available during testing.[1] A higher response accuracy using a single cue indicates a larger *encoding strength.* Second, we examined whether the room size modulated *cue weighting* during test. We examined *cue weighting* by examining *cue preference* when the two cues were in conflict during test. The preferred cue is the cue assigned a heavier weight. And last, we examined whether the room size effect on *cue weighting* could be explained by the room size effect on *encoding strength.*

According to the encoding hypothesis (Figure 1a), the room size directly affects *encoding strength* of the cues but only indirectly affects cue weighting through the *encoding strengths*. Thus, the response accuracy and the cue preference of features relative to geometry should both increase with the room size.

In contrast, according to the retrieval hypothesis (Figure 1b), the room size does not affect the encoding strength but only affects *cue weighting* directly. We note that *encoding strength* probably also affects *cue weighting* (participants would assign a larger weight to the cue that is better learned during encoding). Thus, the cue preference of features should

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[1] Cue salience (encoding strength) can also be measured by cue reliability, which is the inverse of response variance ($\frac{1}{\sigma^2}$), in a study using a continuous response instead of categorical response (e.g. Chen et al., 2017).

increase with the room size but the relative response accuracy of the two cues should not change.

Alternatively, according to the encoding-plus-retrieval hypothesis (Figure 1c), the room size affects both *encoding strength* and *cue weighting* of geometry and features. As *encoding strength* also affects *cue weighting,* this hypothesis, more precisely, claims that the room size affects *cue weighting* both directly and indirectly by affecting *encoding strength*. Thus, both the response accuracy and the cue preference of features relative to geometry should increase with the room size, but with a larger effect on cue preference.

In the current study, we also tested whether familiarity with the environments could modulate the effect of the room size on the relative use of room shape and features. Wang, Mou, and Dixon (2018) reported that *cue weighting* was solely determined by *encoding strength* in unfamiliar rooms; but *cue weighting* was also determined by some retrieval variables (e.g. participants' perception of which cue had been displaced) in familiar rooms. Therefore, if the room size only indirectly affects cue weighting by modulating *encoding strength* according to the encoding hypothesis (Figure 1a), then we should find similar room size effects in both familiar and unfamiliar rooms. If the room size only directly affects *cue weighting* according to the retrieval hypothesis (Figure 1b), then we should observe the room size effect in familiar rooms but not in unfamiliar rooms. If room size affects cue weighting both directly and indirectly according to encoding-plus-retrieval hypothesis (Figure 1c), then we should observe the room size effect in both familiar and unfamiliar rooms, but the effect should be larger in familiar rooms.

General method

Three experiments were conducted to examine the role of familiarity and room size in the relative use of room shape and features during reorientation. The differences in materials, manipulations of familiarity and room size will be discussed in each experiment. Here, we describe the common materials, design, procedure, and the method of data analyses.

Materials and Design

The experiments were conducted in a physical room that was 4 m by 4 m. A swivel chair was placed in the middle of the room. The experiments were implemented in a virtual environment generated using Vizard software (WorldViz, Santa Barbara, CA). A virtual environment was displayed in stereo with an nVisor SX60 head-mounted display (HMD) (NVIS, Inc. Virginia). Participants' head movement was tracked by an InterSense IS-900 motion tracking system (InterSense, Inc., Massachusetts) so that participants could look around in the virtual environment. The virtual environment has a room and two identical features.

Each participant had 32 trials, each consisting of a learning phase and a testing phase. In the learning phase of each trial, participants learned the location of four objects (lock, candle, wood, and bottle) that were located at the four corners of the room. In the testing phase of each trial, participants were required to locate two of the four objects. The locations of the objects differed across trials as in a working memory paradigm (Cheng, 1986).

Participants could rely on two kinds of cues to locate the objects: the room shape, which was a geometric cue; and isolated objects or 2D patterns on the wall, which were featural cues. The room shape was from a rectangular room with walls of 4 m tall. The cue of room shape could be removed by replacing the rectangular room with a square room. The area of the rectangular room and the square room was the same within each experiment. Different from the previous experiments, the featural cues in the current study were two identical landmarks placed in front of, or two identical patterns on two opposite walls. Therefore, both the geometric cue and the featural cues had the same baseline probability of predicting the target (at a 50% chance level).

The learning phases of all 32 trials were the same. Participants learned the location of four target objects with respect to both the rectangular room and the cuing objects/wall features. However, we manipulated the cues presented in the testing phase. There were four conditions (Figure 2): the geometry-only condition, in which only the rectangular room was presented and the features were removed; the feature-only condition, in which the features were presented in a square room; the geometry-and-feature condition, in which both the rectangular room and the features were presented; and the conflict condition, in which both the rectangular room and the features were presented but the features were displaced to the other two walls so that the two cues indicated conflicting orientations. The two single testing cue conditions were used to measure the response accuracy using single cues to infer *encoding strength of individual cues*. The conflict cue condition was used to measure the *cue preferenc*e. The geometry-and-feature condition was also included to test whether these two individual cues were combined additively (Wang, Mou, & Dixon, 2018).

The first 24 trials were randomly assigned to the geometry-only condition, feature-only condition and geometry-and-feature condition, with eight trials for each. The last eight trials were assigned to the conflict condition. The reason the conflict trials were last was that participants may have decided that the cues were unreliable if they found the cues were in conflict, and this might affect their performance in the other conditions in an unpredictable way (Leonard et al., 2018).

In the testing phase of each trial, participants were asked to put two of the four objects back into the original corners. The target objects were chosen at random with the restriction that their locations were not equivalent in terms of their relations to the geometric cue (e.g. both had a short wall on the left and a long wall on the right) or the featural cues (e.g. both were to the left of the features).

Procedure

Wearing a blindfold, participants were guided into the testing room and seated on the swivel chair. Participants donned the HMD and then removed the blindfold. In the learning phase of each trial, participants were released at the center of the virtual room with a random orientation. They were instructed to turn around on the swivel chair to observe the virtual room and learn the locations of four objects which would then be removed and have to be put back. The participants were given 20 seconds to learn the layout. After that, all objects were removed, and the screen turned black for two seconds.

The testing phase started by the presentation of cues. Participants were released at the center of the virtual room with a random orientation. The small model of the probed object was shown at the right bottom corner of the screen. Participants were instructed to put the object back with a pointer by pointing to the correct corner. After the participants responded, the screen turned black for two seconds. The first target object placed by the participants was removed. The participants were then released at the center of the virtual room with a random orientation and were asked to put the second object back. After they had responded for both objects, the screen turned black for two seconds and the next trial began. The participants' responses for both target objects were recorded for each trial.

Note that in the current study, participants sat on the swivel chair through the whole experiment so that they could turn around to observe the room but could not leave the center of the room. Studies with human adults have shown that the room size effect still existed when human adults stood at the center of the room and pointed to the corners (Ratliff & Newcombe, 2008).

Data Analysis

To investigate whether the room size affects the *encoding strengths* of the room shape and the features, we examined the response accuracy of using each single cue. The cue leading to a higher response accuracy would be the cue with a higher *encoding strength*.

We also examined the cue preference in the conflict condition. The proportion of choosing the geometrically correct corner (or the proportion of choosing the featurally correct corner) would measure the cue preference. The proportion of choosing the geometrically correct corner is denoted by $P_{G|Conflict}$. If $P_{G|Conflict}$ was higher than 0.5, the geometry was the preferred cue.

We compared the effect of the room size on the cue preference and on the relative accuracy to infer whether the former was solely determined by the latter in order to differentiate the three hypotheses (Figure 1). Wang, Mou, and Dixon (2018) provided a method to estimate cue preference based solely on response accuracy.

$$predicted\ P_{G|Conflict} = \frac{A_G * (1 - A_F)}{A_G * (1 - A_F) + (1 - A_G) * A_F} \quad (1)$$

The accuracy of localizing the target with geometry only is denoted by A_G. The accuracy of localizing the target with features only is denoted by A_F. The predicted probability of choosing the geometrically correct corner is denoted by predicted $P_{G|Conflict}$. Note that when the response accuracy using the geometry alone (A_G) is larger than the response accuracy using the features alone (A_F), $predicted\ P_{G|Conflict}$ is larger than 0.5, indicating the geometry is the preferred cue. When the response accuracy using the geometry alone (A_G) or the features alone (A_F) is comparable ($A_G = A_F$), $predicted\ P_{G|Conflict}$ is equal to 0.5 indicating neither cue is preferred. Hence, $predicted\ P_{G|Conflict}$ reflects the cue preference that is determined by the relative accuracy.

By contrasting the difference in the observed $P_{G|Conflict}$ with the difference in the predicted $P_{G|Conflict}$ between the rooms, we could determine whether the difference in cue preference was solely determined by the difference in response accuracy between the rooms. Right panels of Figure 1 illustrate the hypothetical relations between patterns of observed cue preferences and predicted cue preference based on relative accuracy of using single cues according to different hypotheses. Consistent with the encoding hypothesis (Figures 1a), the room size effect on the cue preference is solely explained by the room size effect on the cue preference due to the relative *encoding strength* (measured by response accuracy using each single cue). Consistent with the retrieval hypothesis (Figure 1b), as there is no room effect on the relative *encoding strength,* the room size effect on the cue preference is totally independent of the room size effect on the cue preference due to the relative encoding strength. Consistent with the encoding-plus-retrieval hypothesis (Figure 1c), the difference in cue preference between rooms was only partially determined by the difference in cue preference due to the *encoding strength* between the rooms.

In addition, we also examined the combination of cues during retrieval by contrasting the performance in target localization in the geometry-and-feature condition with the sum of the performance in the geometry-only condition and in the feature-only condition using the following equation:

$$predicted\ A_{GF} = \frac{A_G * A_F}{A_G * A_F + (1 - A_G) * (1 - A_F)} \qquad (2)$$

The accuracy of localizing the target in the geometry-only condition is denoted by A_G. The accuracy of localizing the target in the features-only condition is denoted by A_F. The accuracy of localizing the target with both cues is denoted as predicted A_{GF}. Comparable results between the predicted A_{GF} and the observed accuracy in the geometry-and-feature condition would indicate whether geometry and features were combined additively.

Experiment 1

The main purpose of Experiment 1 was to test the three hypotheses. To replicate the room size effect (e.g. Ratliff & Newcombe, 2008), we contrasted wall features with the room shape as cues for reorientation in a small or large room. Participants learned the locations of four objects in a rectangular room with two patterns on two opposite walls.

To test the hypotheses claiming retrieval factors (the retrieval hypothesis and the encoding-plus-retrieval hypothesis), we tested participants in familiar rooms (Wang et al., 2018). The same patterns (features) on the same walls were presented across trials, allowing participants to become familiar with that environment. In a familiar environment, participants encoded the relationships between the room and the wall features. The represented relationships between the room and the wall features could be used to detect the relative displacement between the room and the wall features. Only after participants detected the relative displacement between the room and the features, they could weight cues based on variables (e.g. perception of which cue was displaced) in addition to *encoding strength* following the retrieval hypothesis and encoding-plus-retrieval hypothesis.

Method

Participants. Eighty university students (40 men and 40 women, 19.58±2.15 years old) participated in this experiment as partial fulfillment of a requirement in an introductory psychology course. Sample size was determined based on our previous study (Wang et al., 2018) involving similar within-subject manipulation of environmental cues during reorientation.

Materials, design, and procedure. In addition to the materials, design, and procedure described in the General Method above, the same room and the same wall features appeared across the learning phases of all 32 trials. The wall features were two identical red crosses (Figure 3, upper panel). The relationship between the room and the wall features was also constant across all the trials during learning: the wall features were always in the middle of the two long walls. The wall features were 1.2 m high, approximately at eye level when participants sat on the swivel chair. In the conflict condition, the two wall features were moved to the middle of the two short walls.

The participants were randomly assigned to the small room condition or the large room condition. The small room was 4 m by 8 m. When there was no geometric cue, the rectangular room was substituted by a square room (5.66 m by 5.66 m) of the same area. The large room was 12 m by 24 m, which was nine times larger than the small room. When there was no geometric cue, the rectangular room was substituted by a square room (16.97 m by 16.97 m) of the same area. The wall features in the large room were nine times as large as those in the small room so that they occupied the same area of retinal space.

Results and Discussion

Mean accuracy as a function of testing cue type (geometry-only, feature-only, geometry-and-feature) and room size (small or large) (Figure 4a) was analyzed by mixed-model analyses of variance (ANOVAs), using testing cue type as within-subject variable and room size as between-subject variable. There was only a significant main effect of testing cue type, $F(2, 156) = 7.101$, $p = .001$, $MSE = 0.012$, $\eta_p^2 = 0.083$, whereas the main effect and interaction involving room size was not significant (Fs≤0.208). This result suggests that changing the room size did not affect the participants' response accuracy when reorienting using geometry or features.

The accuracy in all six conditions (combinations of the two independent variables) was above chance level, ts (39) > 8.895, ps < .001. The performance in the geometry-and-feature condition was significantly better than that in the geometry-only condition, $t(79) = 2.958$, $p = 0.004$, Cohen's $d = 0.331$, and in the feature-only condition, $t(79) = 3.715$, $p < 0.001$, Cohen's $d = 0.415$. The latter two did not significantly differ, $t(79) = 0.756$, $p = 0.452$, Cohen's $d = 0.084$. The result shows that the accuracy of reorientation was comparable using individual cues of the room shape and the wall features.

The means of the observed $P_{G|Conflict}$ (the percentage to choose the corner indicated by the geometry in the conflict conditions) and predicted $P_{G|Conflict}$ (using Equation 1) as a function of the room size are plotted in Figure 4b.

Mixed-model ANOVAs showed that the main effect of observation-estimation was not significant, $F(1, 78) = 2.948$, $p = 0.090$, $MSE = 0.061$, $\eta_p^2 = 0.036$. The main effect of the room size was not significant, $F(1, 78) = 2.082$, $p = 0.153$, $MSE = 0.107$, $\eta_p^2 = 0.026$. The interaction between observation-prediction and room size was not significant, $F(1, 78) = 3.248$, $p = 0.075$, $MSE = 0.061$, $\eta_p^2 = 0.040$.

However, planned t tests showed that the observed $P_{G|Conflict}$ was significantly smaller in the large room than in the small room, $t(78) = 2.102$, $p = 0.039$, Cohen's $d = 0.470$. It suggests that participants were more likely to use the wall features in the large room than in the small room, replicating the typical room size effect reported in the literature (e.g., Ratliff &Newcombe, 2008).

Consistent with the result that the room size did not affect the response accuracy using individual cues (cue salience), the predicted $P_{G|Conflict}$ was comparable in different rooms, $t(78) = 0.069$, $p = 0.946$, Cohen's $d = 0.015$. The result that there was a room size effect on the observed $P_{G|Conflict}$ but not on the predicted $P_{G|Conflict}$ suggests that the room size effect on cue preference was not predicted by the room size effect on relative accuracy (*encoding strength*).

Equation 2 was used to test whether the two cues were additively combined in the geometry-and-feature condition. The means of the predicted A_{GF} and of the observed A_{GF} in terms of room size are plotted in Figure 4c and analyzed in mixed-model ANOVAs. The main effect of observation-prediction was significant, $F(1, 78) = 8.500$, $p = .005$, $MSE = 0.009$, $\eta_p^2 = 0.098$. The main effect of the room size was not significant, $F(1, 78) = 0.501$, $p = 0.481$, $MSE = 0.038$, $\eta_p^2 = 0.006$. The interaction between observation-prediction and room size was not significant, $F(1, 78) = 0.091$, $p = 0.763$, $MSE = 0.009$, $\eta_p^2 = 0.001$. These results suggest that the room shape and wall features were not additively combined in either the small or large rooms.

The result that participants were more likely to use featural cues in the large room (Figure 4b) is consistent with the findings in previous studies (e.g. Ratliff & Newcombe, 2008; Sovrano & Vallortigara, 2006; Sovrano, Bisazzaa, & Vallortigara, 2007). However, most of the experiments concerning the room size effect in reorientation used features attached to the wall, such as wall colors, panels or shapes on the wall, or landmarks placed against the wall (see Chiandetti & Vallortigara, 2008 for a review). As defined by Lee and Spelke (2010), both 2D patterns and isolated objects are featural cues as opposed to geometric cues, which are extended surfaces. However, little is known about the difference between 2D patterns and isolated objects. They might be affected in different ways by room size, therefore leading to different trends in room size effects. In Experiment 2, we tested whether the room size effect still exists when we changed the featural cues to isolated objects.

Experiment 2

The purpose of Experiment 2 was to further test the three hypotheses on the room size effect by substituting the featural cues from wall features to isolated objects. Participants learned the locations of four objects in a rectangular room with two cuing objects (Figure 3, lower panels). The same cuing objects were placed at the same location of the room across trials, allowing participants to become familiar with that environment.

We speculate that in Experiment 2, consistent with Experiment 1, the room size would still affect cue preference but not the relative response accuracy (*encoding strength*) of the room shape and the isolated objects. However, we did not have clear predictions on the direction of the room size effect. The results of Experiment 1 suggested that more weight was assigned to the wall features in the large room than in the small room. This might occur because the distance of the wall was further away and the size of the wall is larger in the large room. In contrast, the cuing objects in Experiment 2 were the same size in the large room and in the small room although the distance of them relative to the participants standing at the center was enlarged with the size of the room.

Method

Participants. Eighty university students (40 men and 40 women, 19.15±1.99 years old) participated in this experiment as partial fulfillment of a requirement in an introductory psychology course.

Materials, design, and procedure. The materials, design, and procedure in Experiment 2 were the same as in Experiment 1 except that instead of using wall features, we used isolated cuing objects as featural cues. The cuing objects were two identical traffic cones. The relationship between the room and the cuing objects was constant across all the trials during learning: the traffic cones were always located in front of the two long walls. The center of the traffic cones was aligned with the middle of the two long walls and was 50 cm away from the walls. In the conflict condition, the two traffic cones were moved to the front of the two short walls. The center of the traffic cones was 50 cm away from and aligned with the middle of the two short walls. The traffic cones in the large room were the same size as those in the small room (Figure 3, lower panel).

Results and Discussion

Mean accuracy as a function of testing cue type (geometry-only, feature-only, geometry-and-feature) and room size (small or large) (Figure 5a) was analyzed by mixed-model analyses of variance (ANOVAs), using testing cue type as within-participants variable and room size as between-participants variable. There was only a significant main effect of testing cue type, $F(2, 156) = 26.00$, $p < .001$, $MSE = 0.013$, $\eta_p^2 = 0.250$, whereas the main effect and interaction involving room size was not significant (Fs≤1.219). This result suggests that changing the room size did not affect the response accuracy of reorientation using geometry or features.

The accuracy in all six conditions (combinations of the two independent variables) was above chance level, *t*s (39) > 8.353, *p*s < .001. The performance in the geometry-only condition was significantly worse than that in the geometry-and-feature condition, $t(79) = -2.687$, $p = 0.009$, Cohen's $d = 0.300$. The performance in the feature-only condition was significantly worse than that in the geometry-only condition, $t(79) = -4.838$, $p < .001$, Cohen's $d = 0.541$, and in the geometry-and-feature condition, $t(79) = -6.027$, $p < 0.001$, Cohen's $d = 0.674$. The result shows that reorientation was more accurate using the room shape than using the cuing objects, regardless of the room size.

The means of the observed $P_{G|Conflict}$ and the predicted $P_{G|Conflict}$ as a function of the room size are plotted in Figure 5b.

Mixed-model ANOVAs showed that the main effect of observation-prediction was not significant, $F(1, 78) = 0.899$, $p = 0.346$, $MSE = 0.068$, $\eta_p^2 = 0.011$. The main effect of the room size was not significant, $F(1, 78) = 0.587$, $p = 0.446$, $MSE = 0.085$, $\eta_p^2 = 0.007$. The interaction between observation-prediction and room size was significant, $F(1,78) = 7.331$, $p = 0.008$, $MSE = 0.068$, $\eta_p^2 = 0.086$.

Planned t tests showed that the observed $P_{G|Conflict}$ in the large room was significantly greater than that in the small room, $t(78) = 2.142$, $p = 0.035$, Cohen's $d = -0.479$. It suggests that participants were more likely to use the geometric cue in the large room than in the small room. Consistent with the result that the room size did not affect the response accuracy using individual cues (cue salience), the predicted $P_{G|Conflict}$ was comparable in different rooms, $t(78) = -1.410$, $p = 0.163$, Cohen's $d = 0.314$. The result that there was a room size effect on the observed $P_{G|Conflict}$ but not on the predicted $P_{G|Conflict}$ suggests that the room size effect on cue preference was not predicted by the room size effect on response accuracy (*encoding strength*). The result is consistent with the retrieval hypothesis.

The means of the predicted A_{GF} and of the observed A_{GF} in terms of room size are plotted in Figure 5c and analyzed in mixed-model ANOVAs. The main effect of observation-prediction was significant, $F(1, 78) = 4.990$, $p = .028$, $MSE = 0.009$, $\eta_p^2 = 0.060$. The main effect of room size was not significant, $F(1, 78) = 0.116$, $p = 0.734$, $MSE = 0.033$,

$\eta_p^2 = 0.001$. The interaction between observation-prediction and room size was not significant, $F(1, 78) = 1.053$, $p = 0.308$, $MSE = 0.009$, $\eta_p^2 = 0.013$. These results suggested that room shape and cuing objects were not additively combined in either the small or large room.

We found a room size effect that participants were more likely to use the room shape in the large rooms than in the small rooms. This room size effect is the opposite to the room size effect reported in Experiment 1 and previous studies which found that participants were more likely to use featural cues in larger enclosures (Ratliff & Newcombe, 2008; Sovrano & Vallortigara, 2006; Sovrano, Bisazzaa, & Vallortigara, 2007). We will discuss this discrepancy in the General Discussion.

Experiment 1 and 2 were conducted in familiar rooms where the participants could learn the relationship between the cues. With this knowledge, they could detect the conflict when the cues were displaced. Therefore, they should not only weigh the cues based on the *encoding strengths* of the cues but also based on other variables (e.g. determining which cue had been moved) (Wang et al., 2018). In an unfamiliar room, however, participants could not learn the relationship between the cues and thus could not detect the conflict between the cues. As a result, cue preference should be solely determined by the encoding strengths of the cues. To extend the results of Experiment 1 and 2, we conducted Experiment 3 where participants reoriented themselves in a small or large unfamiliar room. If the room size did not affect *encoding strength* according to the retrieval hypothesis (Figure 1b), we should not observe any room size effect in Experiment 3.

Experiment 3

Experiment 3 investigating the cue preference of room shape and isolated objects during reorientation in a small or large unfamiliar room. Unlike in Experiment 2, in which the appearance of the room, the cuing objects, and their relative locations were the same across trials, we used eight rooms of different sizes and with different colors, and four different cuing objects, and changed the relative location between the rooms and the cuing objects from trial to trial in Experiment 3. As the environment changed from trial to trial, participants experienced a novel environment in every trial.

Method

Participants. Eighty university students (40 men and 40 women, 18.74±2.10 years old) participated in this experiment as partial fulfillment of a requirement in an introductory psychology course.

Materials, design, and procedure. The material and design in Experiment 3 were the same as in Experiment 2 except for the following change: in Experiment 3, the virtual environment in each trial was novel. For each room size condition, we used four different cuing objects and eight rooms with different colors and different length ratios of the short walls to the long walls (1:1.5, 1:1.8, 1:2.1, 1:2.4, 1:2.7, 1:3, 1:3.3, 1:3.6), keeping the area of the rooms 32 square meters for the small room condition (4.62 m * 6.92 m, 4.22 m * 7.6 m, 3.9 m * 8.2 m, 3.66 m * 8.76 m, 3.44 m * 9.3 m, 3.26 m * 9.8 m, 3.12 m * 10.28 m, 2.98 m * 10.74 m) and 288 square meters for the large room condition (13.86 m * 20.76 m, 12.66 m * 22.8 m, 11.7 m * 24.6 m, 10.98 m * 26.28 m, 10.32 m * 27.9 m, 9.78 m * 29.4 m, 9.36 m * 30.84 m, 8.96 m * 32.22 m), the same as in Experiment 2. The cuing objects were two traffic cones, two potted plants, two vases, or two baskets. Thus, we created 32 different environments (combinations of four cuing objects and eight rooms) for each room size condition. We assigned each environment to one of the 32 trials so that environments in all 32 trials were different. Furthermore, the location of the cuing objects with respect to the room was randomly chosen between two options for each trial: the cuing objects were located either in front of the two short walls or in front of the two long walls. The 32 environments were randomly assigned into the four conditions with the restriction that each room was used once in each condition.

Results and Discussion

Mean accuracy as a function of testing cue type (geometry-only, feature-only, geometry-and-feature) and room size (small or large) (Figure 6a) was analyzed by mixed-model analyses of variance (ANOVAs), using testing cue type as within-participants variable and room size as between-participants variable. There was only a significant main effect of testing cue type, $F(2, 156) = 32.572$, $p < .001$, $MSE = 0.017$, $\eta_p^2 = 0.295$, whereas the main effect and interaction involving room size was not significant (Fs≤0.975). This result suggests that changing the room size did not affect the response accuracy of the reorientation using either geometry or features.

The accuracy in all six conditions (combinations of the two independent variables) was above chance level, ts (39) > 5.121, ps < .001. The performance in the feature-only condition was significantly worse than that in the geometry-only condition, $t(79) = 6.075$, $p < 0.001$, Cohen's $d = 0.679$, and in the geometry-and-feature condition, $t(79) = 6.458$, $p < 0.001$, Cohen's $d = 0.722$. The latter two did not significantly differ, $t(79) = 0.373$, $p = 0.710$, Cohen's $d = 0.042$. The result shows that reorientation using the room shape was more accurate than that using the cuing objects.

The means of the observed $P_{G|Conflict}$ and predicted $P_{G|Conflict}$ as a function of the room are plotted in Figure 6b.

Mixed-model ANOVAs showed that the main effect of observation-prediction was not significant, $F(1, 78) = 1.657$, $p = 0.202$, $MSE = 0.080$, $\eta_p^2 = 0.021$. The main effect of the room size was not significant, $F(1, 78) = 0.214$, $p = 0.645$, $MSE = 0.073$, $\eta_p^2 = 0.003$. The interaction between the observation-prediction and room size was not significant, $F(1,66) = 0.054$, $p = 0.817$, $MSE = 0.080$, $\eta_p^2 = 0.001$.

Planned t tests also showed that the observed $P_{G|Conflict}$ in the small rooms was not significantly different from that in the large rooms, $t(78) = 0.149$, $p = 0.99$, Cohen's $d = 0.033$. Consistent with the result that the room size did not affect the response accuracy using individual cues (cue salience), the predicted $P_{G|Conflict}$ was comparable in different rooms, $t(78) = 0.497$, $p = 0.621$, Cohen's $d = 0.111$.

The means of the predicted A_{GF} and of the observed A_{GF} in terms of room size are plotted in Figure 6c and analyzed in mixed-model ANOVAs. The main effect of observation-prediction was significant, $F(1, 78) = 7.682$, $p = 0.007$, $MSE = 0.012$, $\eta_p^2 = 0.090$. The main effect of the room size was not significant, $F(1, 78) < 0.001$, $p = 1.000$, $MSE = 0.036$, $\eta_p^2 < 0.001$. The interaction between observation-prediction and room size was significant, $F(1, 78) = 4.617$, $p = 0.035$, $MSE = 0.012$, $\eta_p^2 = 0.056$. A simple effect analysis showed that in the small room, the observed accuracy of the geometry-and-feature condition was significantly lower than predicted, $t(39) = -3.732$, $p = 0.001$, Cohen's $d = -0.590$, whereas in the large room, the observed and predicted accuracy of the geometry-and-feature condition was not significantly different, $t(39) = -0.414$, $p = 0.681$, Cohen's $d = 0.065$.The results suggest that the room shape and cuing objects were additively combined in the large room but not in the small room.

Unlike Experiment 2, the results of Experiment 3 showed that the room size did not affect the cue preference in unfamiliar rooms. Similar to Experiment 2, the results of Experiment 3 showed that the room size did not affect the relative response accuracy.

General Discussion

This study tested three hypotheses on how the room size affects cue preference while human adults use geometric and featural cues for reorientation inside rooms. It could be that the room size affects using cues in encoding participants' orientation (encoding hypothesis), in retrieving participants' orientation (retrieval hypothesis), or both (encoding-plus-retrieval hypothesis). There are three important findings. First, room size did not affect the relative accuracy (*encoding strength*) using the room shape and isolated objects or using the room shape and wall features regardless of whether participants were familiar or unfamiliar with the rooms. Second, in familiar rooms, the wall features were more preferred in the large room than in the small room, whereas the isolated cuing objects were less preferred in the large room than in the small room relative to the room shape. Third, the room size did not affect the cue preference in unfamiliar rooms.

Most importantly, these findings strongly support the retrieval hypothesis. There was no evidence suggesting that the room size affected the *encoding strength* of each cue. We used the response accuracy of using each cue as an indicator of *encoding strength*. In all the experiments, the response accuracy of using room shape, isolated objects, or wall features in the small rooms was not significantly different from that in the large rooms. Consistently, the predicted $P_{G|conflict}$ based on the relative response accuracy of using each cue in the small rooms was comparable to that in the large rooms.

These findings did not support that the room size effect is due to a positive relationship between the salience of features and room size (Miller, 2009) or a negative relationship between the salience of geometry and room size (Sovrano & Vallortigara, 2006). In Experiment 1, the large rooms were nine times as big as the small rooms, and the wall features in the large rooms were also nine times as big as those in the small rooms so that the wall features occupied the same area of retinal space regardless of room size. In Experiments 2 and 3, the large rooms were nine times as big as the small rooms, whereas the absolute size of the isolated cuing objects was the same in the small room and in the large room. Nevertheless, change in room size did not affect encoding accuracy in all the three experiments. These results suggest that, at least for human adults, the relative size of features to geometry may not be critical to assigning resources to encode the orientation relative to different cues.

Note that we could not conclude that the cue salience did not change with room size although *encoding strength* did not change with room size. Within the current paradigm, the encoding strength may not be sensitive enough to detect the difference in cue salience. Although the current study used the overshadowing paradigm, we cannot exclude the possibility that overshadowing was not complete so that participants still had encoded both cues. Future studies are needed to examine the relationship among encoding strength, cue salience and room size in a carefully controlled overshadowing paradigm (Buckley, Smith, & Haselgrove, 2015; Buckley, Smith, & Haselgrove, 2014; Kosaki, Austen, & McGregor, 2013).

While the encoding strength was not sensitive to room size, we observed that the room size affected cue preference in the familiar rooms. In particular, as the room size increased, the relative use of wall features over the room shape increased whereas the relative use of isolated objects over the room shape decreased. These results support the retrieval hypothesis stipulating that the room size only affects the *cue weighting* process during retrieval but does not affect the *encoding strength* of the cues. We acknowledge that the null effect of room size on encoding strength might be partially attributed to the specific design of the current study. We always placed the conflict trials in the end. Therefore, although the discrepancy of these two cues affect cue preference in the conflict trials, it cannot affect encoding in other trials, especially the single testing cue trials. In future studies, we may place the conflict trials before other trials and see if the room size also affects encoding strength.

According to the adaptive combination theory, the weighting of cues may depend on various factors such as cue salience and cue stability (Newcombe & Huttenlocher, 2006). However, it is not clear whether these factors play a part in the room size effect in reorientation. Based on our result and previous studies (Miller, 2009; Nadel & Hupbach, 2006; Sovrano & Vallortigara, 2006; Wang, Mou, & Dixon, 2018), we will discuss two possibilities: first, the room size effect on cue preference is due to the effect of cue salience on cue weighting; second, the room size effect on cue preference is due to the effect of cue stability on cue weighting.

The first possibility could explain the result of Experiment 2. In Experiment 2, the cuing objects were less salient in the larger room comparing to geometry because the absolute size of the objects remained the same while the room size was larger. Therefore, the participants relied less on the cuing objects in larger rooms in the conflict condition. However, this possibility cannot explain the result of Experiment 1. While the size of the room and the wall features increased with the same ratio, their relative salience should not change with room size. However, the participants relied more on the wall features in larger rooms in the conflict condition.

The second possibility, i.e. the room size effect on cue preference is due to the effect of cue stability on cue weighting, is more plausible. The current study showed that the cue preference was modulated by the room size in familiar environments but not in unfamiliar environments. In unfamiliar environments, participants did not learn the relationship between the room shape and the cuing objects, and thus could not detect the conflict between the two cues (Wang, Mou, & Dixon, 2018). Therefore, their preference of the cues was only determined by cue strength. In contrast, in familiar environments, the participants learned the relationship between the room shape and the cuing objects. Therefore, they noticed that the two cues were moved relatively and they had to judge which cue was moved. In this case, their cue preference might have been affected by the stability of the cues (Cheng et al., 2007; Wang et al., 2018). Consequently, if the room size affects cue preference by only modulating cue weighting rather than encoding strength according to the retrieval hypothesis, then the room size effect on the cue preference should occur only in the familiar room but not in unfamiliar room. Thus, the finding that the cue preference was modulated by the room size in familiar environments but not in unfamiliar environments is consistent with this possibility.

It is striking that while wall features were more preferred in the large room than in the small room (the typical room size effect), the isolated objects were less preferred in the large room than in the small room (the reversed room size effect). To our knowledge, the current study, for the first time, indicates that the direction of the room size effect (typical or reversed) relied on the type of features.

One explanation of the typical room size effect (Experiment 1) is that a distal landmark is more stable than a proximal landmark because it is less vulnerable to the observers' movements (Nadel & Hupbach, 2006). This speculation should be modified to explain the reversed room size effect. We speculate that cue stability during retrieval could be attributed not only to cue distance but also to the movability of cues. The movability of a cue may be partially determined by the size of the cue. For example, in our study, a small traffic cone (one isolated object) is more likely to be moved than a huge room. The movability of a cue may also be determined by how it is connected to other cues. For example, in our study, an isolated traffic cone can easily be moved, whereas moving a wall feature is more difficult because it involves erasing the feature from one wall and painting it on another wall. Moreover, the wall feature may be used to specify the identity of the wall. When we changed a wall feature from one wall to another, it is possible that the participants did not think the feature itself moved, but that the wall with that feature moved. In this case, the movability of a wall feature is equivalent to the movability of the wall having that feature.

Specifically, in Experiment 1, the wall features (or the walls having those features) and the room were scaled with the same ratio. Therefore, the relative movability of the room and the wall features should not have been affected by the room size. Thus, the room size affected the relative stability of the cues by affecting the distance of the wall features to the observer as originally proposed by Nadel and Hupbach (2006). In Experiment 2, while the traffic cones did not change their size, the room size increased significantly in the large room. Assuming that the relative movability negatively relates to the relative size, the relative movability of the room decreased in the large room. Assuming the effect of room movability overwhelmed the effect of feature distance on the relative stability of the cues, it can explain the reversed room size effect. The reversed room size effect may also be attributed to the change of the relative salience of objects and the room in different rooms. An object did not change its absolute size but its relative size decreased in the large room. Therefore, the object appeared to be less salient in the large room. As we discussed above, however, this explanation cannot explain the typical room size effect in Experiment 1. Note that in the current study, we did not deliberately define or manipulate the stability of the cues. Future studies are needed to systematically test the role of cue stability and cue salience in the room size effect during reorientation.

In reorientation studies, wall features (such as the color) and isolated objects were commonly used as featural cues to contrast with geometric cues. Wall features and isolated objects were treated as the same type of cues because they were found to be less dominant than the room shape during reorientation (for reviews, see Cheng & Newcombe, 2005; Vallortigara, 2009). However, the different patterns of room size effects found in the current study suggest that it may be important to differentiate wall features and isolated objects in reorientation studies, at least when investigating the room size effect.

It is worth noting that the room size effect during reorientation of children may not share the same mechanism as the room size effect during reorientation of human adults. For example, Learmonth and colleagues (2008) found that the room size effect was eliminated when the children were restricted at the center of the room. However, the current study and previous studies (Ratliff & Newcombe, 2008) showed that the room size still existed when human adults were restricted at the center of the room. We speculate that the main difference between children and human adults in this case is that young children might not be able to effectively evaluate cue stability (Heth et al., 1997) and rely more on encoding strengths of individual cues. Therefore, the encoding hypothesis instead of the retrieval hypothesis may apply to children. Future studies should test the three hypotheses for children's reorientation by examining both the room size effect on *encoding strength* and *cue weighting* as in the current study.

In sum, the current study contributed to the understanding of the room size effect on reorientation using geometric and featural cues. We showed that in familiar rooms, the room size affected the cue preference but did not affect the relative accuracy using single cues, whereas in unfamiliar rooms, the room size did not affect the relative accuracy using single cues or the cue preference. Therefore, we concluded that the room size affected the cue preference by affecting cue weighting during retrieval, but not by affecting encoding strength.

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Declarations of interest: none.

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Figure Captions

Figure 1. Three hypotheses on the room size effect: a) The encoding hypothesis. b) The retrieval hypothesis. c) The encoding-plus-retrieval hypothesis.

Figure 2. Examples of the within-subject conditions in all the experiments. The blue bars denote the featural cues. Four objects were located at the four corners respectively. X denotes the location or the equivalent location for one target object.

Figure 3. Examples of experimental environment from participants' view. Upper left: small room with wall features. Upper right: large room with wall features. Lower left: small room with cueing objects. Lower right: large room with cueing objects.

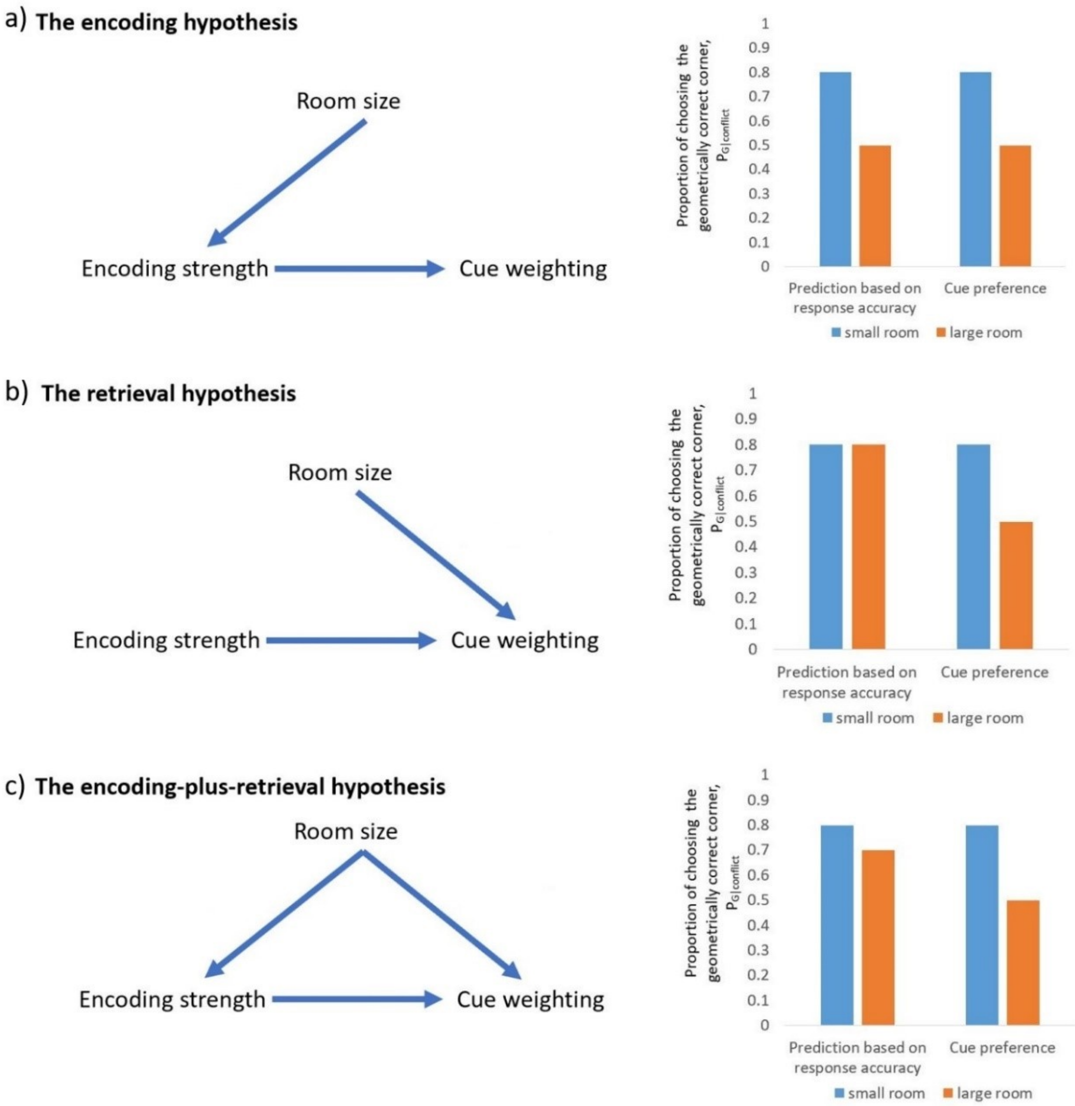
Figure 4. a) Proportion correct in locating target objects as a function of testing cue type and room size in Experiment 1. b) The observed and estimated percentage of choosing the response location indicated by the room shape when the room shape and the wall features were in conflict ($P_{G|Conflict}$) as a function of room size in Experiment 1. c) Observed and estimated proportion correct in locating target objects when both the room shape and the wall features indicated the same orientation (A_{GF}) as a function of room size in Experiment 1. Error bars represent standard errors of the mean.

Figure 5. a) Proportion correct in locating target objects as a function of testing cue type and room size in Experiment 2. b) The observed and estimated percentage of choosing the response location indicated by the room shape when the room shape and the cuing objects were in conflict ($P_{G|Conflict}$) as a function of room size in Experiment 2. c) Observed and estimated proportion correct in locating target objects when both the room shape and the

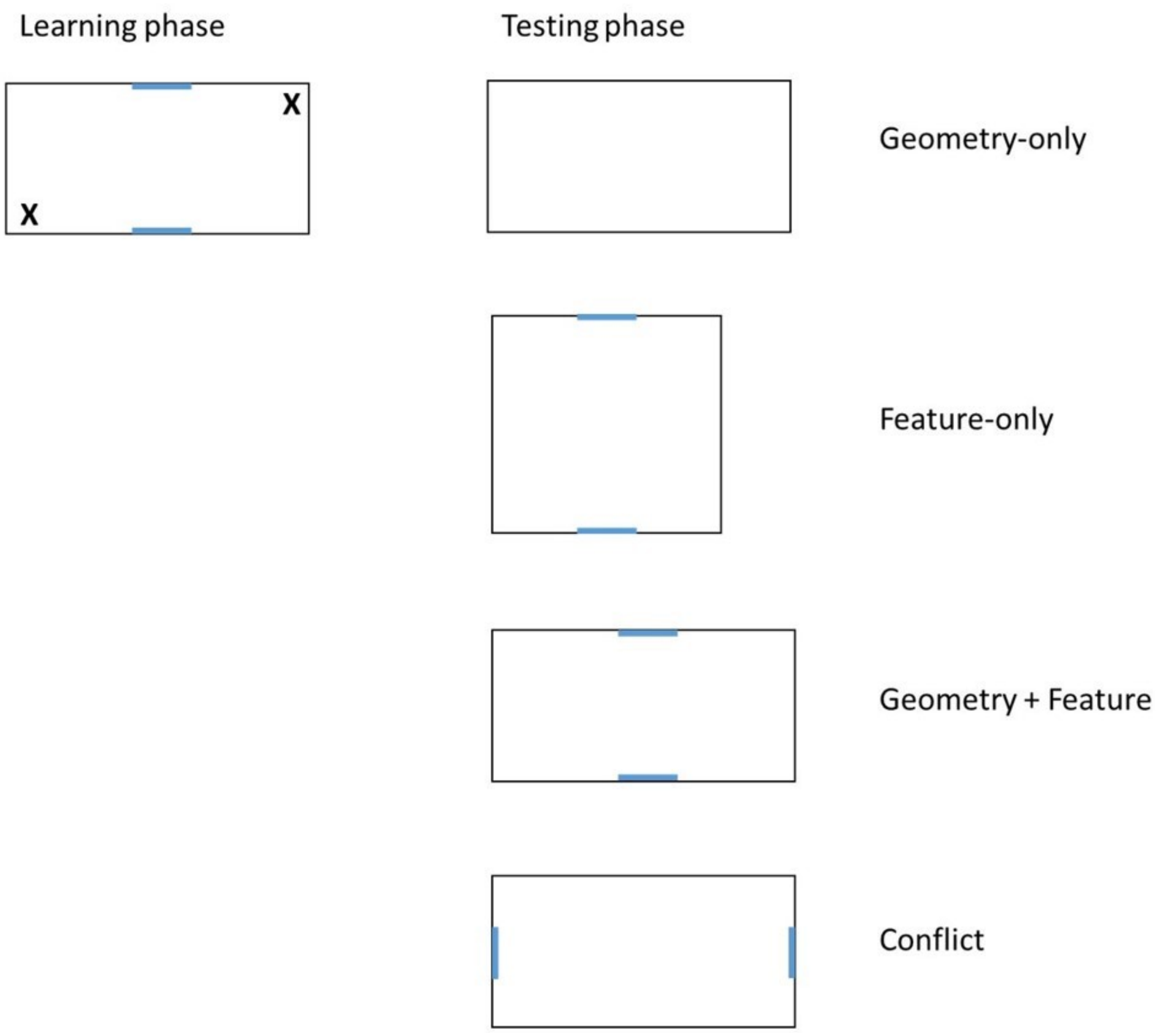
cuing objects indicated the same orientation (A_{GF}) as a function of room size in Experiment 2. Error bars represent standard errors of the mean.

Figure 6. a) Proportion of choosing the correct corners as a function of testing cue type and room size in Experiment 3. b) The observed and estimated percentage of choosing the corners indicated by the room shape when the room shape and the cuing objects were in conflict ($P_{G|Conflict}$) as a function of room size in Experiment 3. c) Observed and estimated proportion of choosing the correct corners when both room shape and cuing objects indicated the same orientation (A_{GF}) as a function of room size in Experiment 3. Error bars represent standard errors of the mean.

Figure 1.


a) The encoding hypothesis
Room size
Encoding strength
Cue weighting
Proportion of choosing the geometrically correct corner, P G|conflict
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Prediction based on response accuracy
Cue preference
small room
large room
b) The retrieval hypothesis
Room size
Encoding strength
Cue weighting
Proportion of choosing the geometrically correct corner, P G|conflict
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Prediction based on response accuracy
Cue preference
small room
large room
c) The encoding-plus-retrieval hypothesis
Room size
Encoding strength
Cue weighting
Proportion of choosing the geometrically correct corner, P G|conflict
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Prediction based on response accuracy
Cue preference
small room
large room

1 Figure 2.



Learning phase
Testing phase
X
X
Geometry-only
Feature-only
Geometry + Feature
Conflict

2

Figure 3.

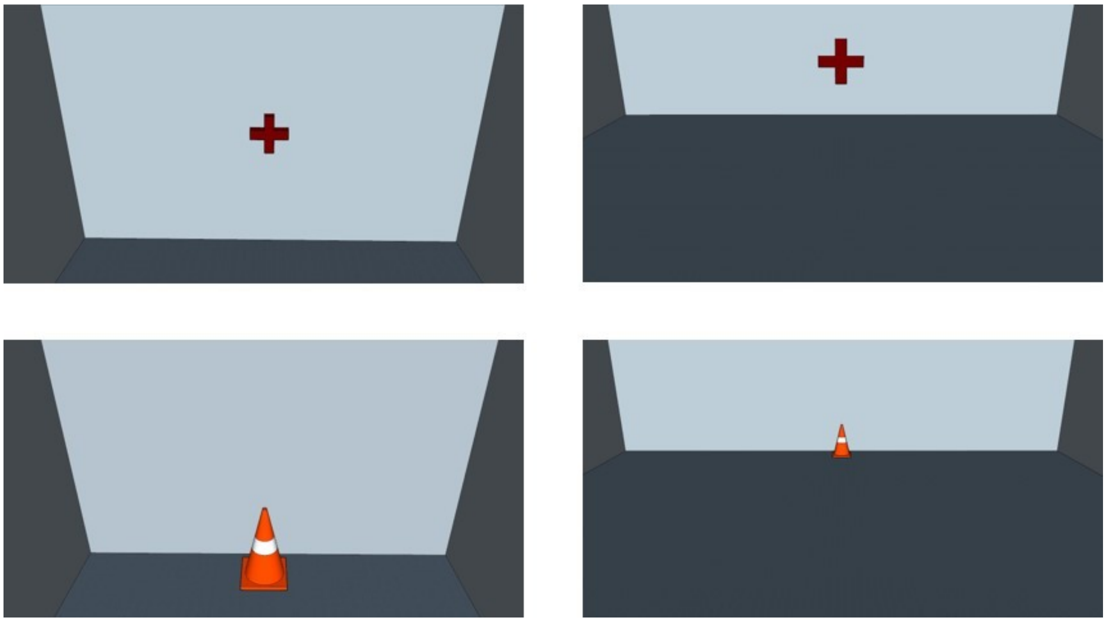


Figure 4.

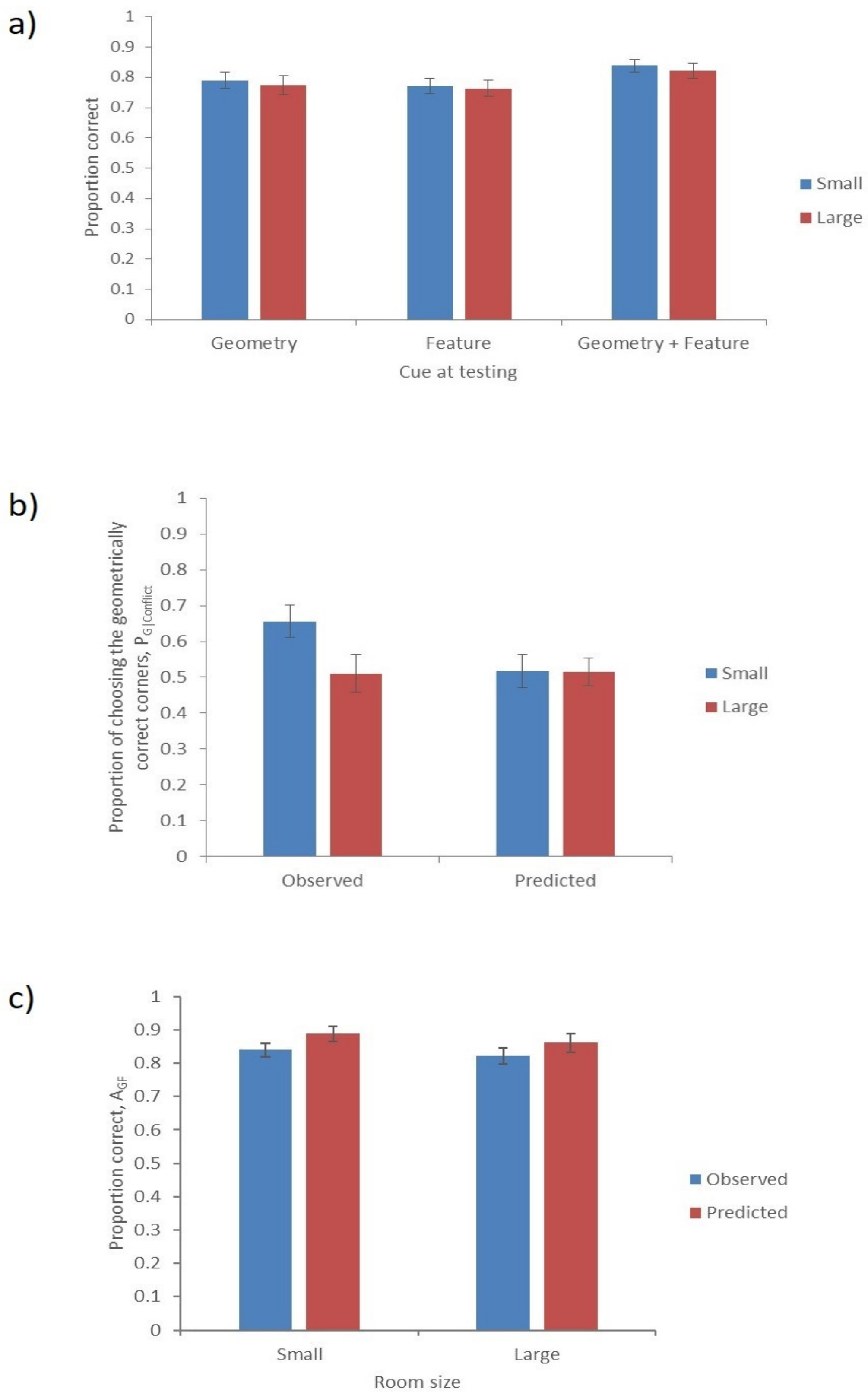

a)
Proportion correct
Geometry
Feature
Geometry + Feature
Cue at testing
Small
Large
b)
Proportion of choosing the geometrically correct corners, $P_{G|Conflict}$
Observed
Predicted
Small
Large
c)
Proportion correct, A_{GF}
Small
Large
Room size
Observed
Predicted

Figure 5.

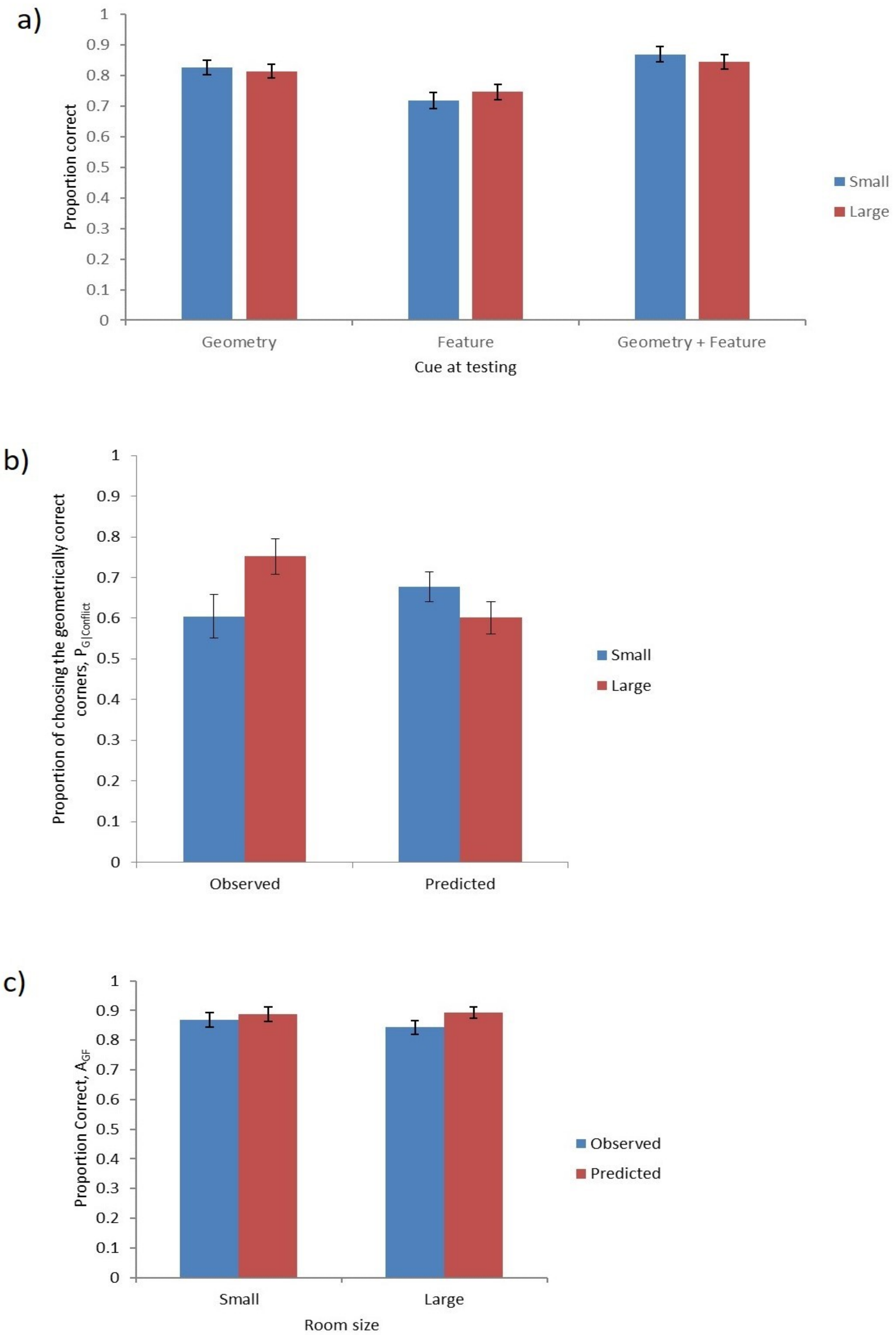
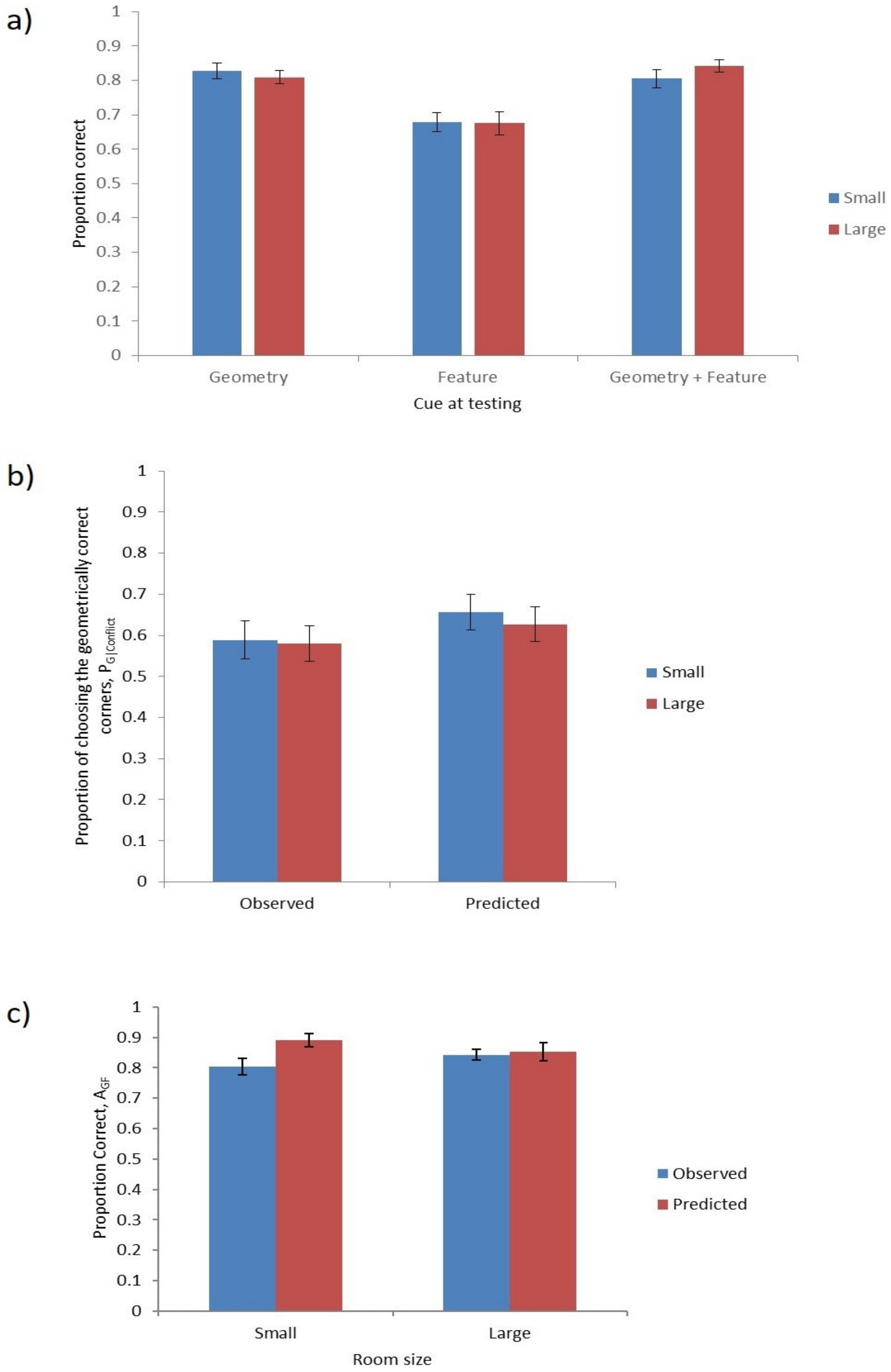

a)
Proportion correct
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Geometry
Feature
Geometry + Feature
Cue at testing
Small
Large
b)
Proportion of choosing the geometrically correct corners, $P_{G|Conflict}$
Observed
Predicted
Small
Large
c)
Proportion Correct, A_{GF}
Small
Large
Room size
Observed
Predicted

Figure 6.


a)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Proportion correct
Geometry
Feature
Geometry + Feature
Cue at testing
Small
Large
b)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Proportion of choosing the geometrically correct corners, P G|Conflict
Observed
Predicted
Small
Large
c)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Proportion Correct, A GF
Small
Large
Room size
Observed
Predicted