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Spatial Updating in Intrinsic Frames of Reference

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Abstract

The present study investigates the properties of the spatial updating in terms of intrinsic frames of reference. We hypothesize that the efficiency of dynamically updating object-to-object relations is based on two main factors, a relatively stable frame of reference provided by the orienting object (or object array), and the behavioral significance (salience) level of the target objects. Three experiments were conducted using tasks of direction pointing. It was found that responses were significantly slower when the orienting object was constantly rotating. Given a relatively stable frame of reference, responses to the salient objects were faster than those to the non-salient objects when the number of salient objects was limited. The salience effect disappeared and reappeared in the absence and presence of a stable frame of reference, respectively. These findings indicated that spatial updating in intrinsic frame of reference is not automatic and is limited by the number of target objects.

Introduction

As people move through an environment, they continuously update the spatial relations between themselves and the environment and the relations between the objects in the environment. For instance, a pedestrian who is waving on a taxi may also notice that a dog is chasing the taxi from behind. In this scenario, two kinds of information have to be encoded by the pedestrian, the relation between his body and the taxi, and the relation between the taxi and the dog. In fact, this example illustrates the distinction between an egocentric reference system (body-centered) and an allocentric reference system (more specifically in this scenario, an object-centered intrinsic system). It has been generally agreed that in encoding spatial information, different reference systems can be involved. Many researchers adopted the distinction between egocentric and allocentric reference systems and conjectured that participants in their experiments used either one of such systems (e.g., Bryant & Tversky, 1999; Diwadkar & McNamara, 1997; Franklin & Tversky, 1990; Shelton & McNamara, 1997; Sholl & Nolin, 1997; Simons & R. Wang, 1998. For a recent treatment, see McNamara, 2003, and Mou & McNamara, 2002).

A large body of research has been focusing on spatial updating with respect to the egocentric system. It has been indicated that spatial memories are primarily egocentric and updating by the egocentric system is of high fidelity and automatic (e.g., Rieser, 1989; Shelton & McNamara, 1997; Simons & R. Wang, 1998; R. Wang, 1999). Nevertheless, Mou and McNamara (2002) and McNamara (2003) recently proposed that spatial information is encoded primarily of object-to-object spatial relations, and therefore is allocentric. This new theoretical framework calls for a systematic study on properties of spatial updating in intrinsic systems in dynamic situations, as compared to updating in egocentric systems. For example, Sholl and Nolin (1997) and R. Wang (1999) have suggested that egocentric self-to-object spatial relations are updated automatically as people move through an environment. It remains unclear whether updating in intrinsic frame of reference is also automatic. Furthermore, what kind of information is to be updated in intrinsic systems? Are all objects in the environment being updated with equal priorities? The present paper attempts to answer these questions by reporting three experiments.

Our working hypothesis on spatial updating in intrinsic frame of reference is that such a process involves paying attention to both the orienting objects that anchor the intrinsic frame of reference and the target objects in their relations to the orienting objects. In other words, there are two sequential components in such a process: establishing and maintaining a frame of reference, then, updating the object-to-object relations. Thus, we hypothesize that updating in intrinsic systems can be achieved dynamically only when a relatively stable frame of reference can be maintained. In the taxi example above, in order to update the relations between the taxi and the dog, the pedestrian first needs to identify the orientation of the taxi. Second, we hypothesize that updating of object-to-object relations is affected by the behavioral significance of the target objects. This hypothesis is based on previous findings that visual selection can be prioritized by the object's properties, by its specific location and background (e.g., Duncan, 1984; Wolfe, 1994), or even by cues in time (e.g., Watson, Humphreys, & Olivers, 2003). In the taxi example, a dog chasing the taxi probably is more salient than other objects on the street (say, a post stand), thus it is more likely to be

attended to continuously by the pedestrian. We will refer to this effect as the “salience effect” throughout this paper.

We conducted three experiments to test our hypotheses. The task we used was similar to the direction pointing task in the visual map condition in Hintzman, O’Dell, and Arndt (1981). Two major modifications were made to fit our specific needs. First, we added settings to test the salience effect. That is, the target objects had two different salience levels, determined by both behavioral and perceptual significance. Second, to test real-time updating, our experiments were implemented in dynamic settings, which involved continuous relative movement between the orienting object (intrinsic frame of reference) and the target objects. We tested three different movements: the translation-only movement (Experiment 1), the movement in which the orienting object rotated while the target objects remained still (Experiment 2), and the movement in which the orienting object remained still but the target objects rotated (Experiment 3).

General Method

Since all three experiments reported here shared similar settings and procedures, we summarize the common aspects of the experimental settings and data analyses in this section. The experiments were conducted on a Pentium II computer, and the stimuli were presented on a 19-inch CRT monitor. The stimuli consisted of one blue submarine image (bird’s eye view) and a certain number of white dots (non-salient objects) and red dots (salient-objects) on a grey background. All three experiments used a 2x8x8x2 within-subjects design, in which there were two salience levels (salient vs. non-salient), eight submarine orientations, eight target directions, and two levels for the number of salient objects. Each participant completed 256 trials, with each trial representing one combination of all levels of all factors. The order of the 256 trials was randomly shuffled. A trial consisted of three steps. First, the submarine and the surrounding dots were presented and the submarine flashed three times to help participants identify its location and orientation. Then, depending on the specific experiment, either the submarine or the surrounding dots started to move (translating or rotating). Finally, the relative movements stopped and at the same time one of the surrounding dots flashed as the target. The instruction for all three experiments was the same. Participants were instructed to imagine being on the submarine and an enemy submarine (the target) was hiding at the location of one of those surrounding dots. The red dots were more likely to be enemy positions thus participants should pay particular attention to them. When the target flashed, participants were told to indicate the direction of the target relative to the orientation of the submarine.

The responses were made with a number keypad on a standard PC keyboard. On the keypad, the number keys 1, 2, 3, 4, 6, 7, 8, and 9 were used as response keys, with each representing one of the eight directions relative to key 5. These keys were re-labeled with drawings of arrows

pointing to the corresponding directions. All other keys were removed and the key for number 5 (which was in the center of all eight response keys) was replaced with a stud that could not be pressed. Participants were instructed to use only one finger to press the response keys. At the beginning of each trial, they were told to rest the finger on the stud, and after they made the response, to put the finger back on the stud.

The primary dependent measure was the reaction times (RT) measured in milliseconds. To avoid confusion, we adopted the same labeling scheme as used in Hintzman et al. (1981). Descriptive names were used for responses (target direction relative to the submarine’s orientation), such as front, right-front, right, right-back, back, left-back, left, and left-front. For submarine orientation (equivalent to the arrow orientation in Hintzman et al.’s experiment 1 and 2), we used digits 0 through 7, representing the number of steps by 45° clockwise from upright (e.g., digit 0 for the upright submarine orientation, and digit 4 represents the downright orientation).

Experiment 1

Participants Twelve college students and graduate students in the Houston medical center area participated in Experiment 1 (six males and six females, and the average age was 29.3 years with an SD of 4.81 years). Participants were paid for participation.

Procedure Figure 1 shows a typical display in Experiment 1. At the beginning of each trial, one blue submarine image and 400 dots (in which 2 or 4 of them were red and the rest were white) arranged in a 20 x 20 array were presented simultaneously. Red and white dots were the same size, with a diameter of approximately 0.40 cm. The horizontal and vertical distance between every adjacent two dots (hence referred to as one unit) was approximately 0.85 cm, and the submarine image, when upright, was approximately 0.80 cm high and 0.44cm wide. The salient objects were randomly plotted (without overlapping with each other) within a 5 by 5 array in the center of the entire array. The initial position of the submarine was 4, 5 or 6 units (randomly selected) away from the center of the array, randomly taking one of the 8 possible orientations but always approximately pointing to the center of the dot array.

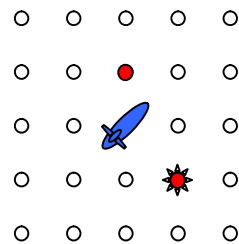


Figure 1

At the beginning of each trial, the submarine flashed three times and then started to move (translation without rotation)

toward the center of the array. The moving speed was constant for all trials, which was approximately 2136 ms per unit (0.47 units per second). When the submarine reached approximately the center of the array, it would stop and at the same time, one of the eight dots in the 3 by 3 square where the submarine was located would flash (the submarine image covered the dot in the center of the square). Participants pressed the response key to respond to the target direction relative to the submarine. The accuracy and reaction times were recorded. A regular experimental session took approximately one and a half hour (in which the training session took approximately 20 minutes).

Results The mean RT for the 12 participants was 1247.4ms with a standard deviation of 542.40ms. The mean accuracy rate was 93.5% with a standard deviation of 4.56%. RT as a function of the target direction is shown in Figure 2, and RT as a function of the submarine orientation is shown in Figure 3, with RT broken down by two salience levels, where error bars represent standard errors. The target names in Figure 2 are abbreviated (F for Front, FR for Right Front, etc.). To emphasize the symmetry and continuity, the direction F in Figure 2 and the orientation 0 in Figure 3 were represented twice. This convention is used in other similar figures throughout this paper.

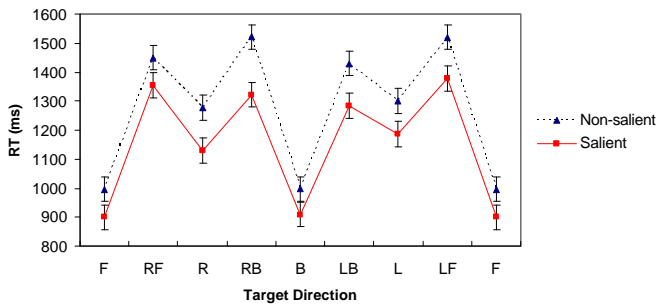


Figure 2. Experiment 1, RT as a function of target direction.

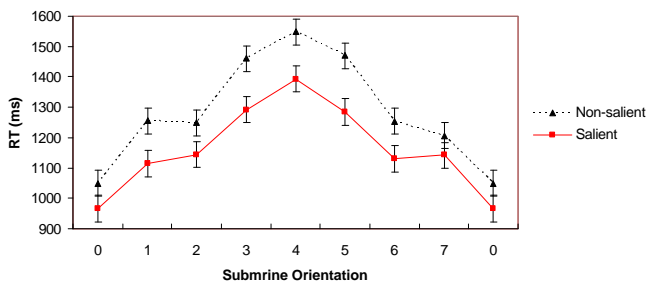


Figure 3. Experiment 1, RT as a function of submarine orientation.

A significant orientation effect was observed. RT as a function of the target direction showed an “M” shaped profile, fastest on the front and back directions and slowest on the right-back and left-back directions ($F_{7, 77} = 16.14$, $p < .001$, estimated effect size = .595). As a function of

submarine orientation, RT was fastest when the submarine was upright (orientation 0), and slowest when the submarine was pointed down (orientation 4) ($F_{7, 77} = 16.74$, $p < .001$, estimated effect size = .603).

Of primary interests to us was the salience effect. It is clear from both Figures 2 and 3 that the salience level had a significant effect on RT. In all target directions and submarine orientations, responses to salient objects were faster than that of non-salient objects, with an average difference of 128.6 ms ($F_{1, 11} = 27.95$, $p < .001$, estimated effect size = .718). Moreover, the salience effect appeared to be very stable in size across all target directions and submarine orientations: the two curves in each figure are essentially parallel, and both interactions (salience by target direction, and salience by submarine orientation) were not significant ($F_{7, 77} = 1.185$, $p = .321$; and $F_{7, 77} = 1.471$, $p = .190$, respectively).

The number of salient objects (hence abbreviated as NOS) appeared to have a small effect on RT. On average, RT was faster when NOS = 2 than when NOS = 4 (mean difference = 26.5 ms), which was marginally significant ($F_{1, 11} = 4.57$, $p = .056$). The effect of NOS would be observed more clearly through the interaction between NOS and salience, which was statistically significant ($F_{1, 11} = 6.09$, $p = .031$, estimated effect size = .356). It appeared that NOS had little effect on RT when the target was a non-salient object (1314.9 ms when NOS = 2, compared to 1308.3 ms when NOS = 4), but the effect was considerably larger when the target was a salient object (1153.3 ms when NOS = 2, compared to 1212.9 ms when NOS = 4, mean difference = 59.6 ms).

Other factors remaining constant, faster RT for the salient objects in Experiment 1 suggests that spatial information about salient objects was updated with a higher priority thus retrieved more quickly than the information about the non-salient objects. Moreover, the orientation dependence was presented in responses to both salient objects and non-salient objects: both main effects of target direction and submarine orientation were significant but none of the interactions (target direction and salience, submarine orientation and salience, respectively) reached significance, implying the important role the orientation plays in spatial updating.

Furthermore, it is interesting to note that the salience effect remained but reduced in size when the number of salient objects increased (from 161.6 ms when NOS = 2, to 95.4 ms when NOS = 4). One explanation is that more than four salient objects were prioritized but the retrieval of the corresponding information was achieved in a serial fashion. Another explanation is that the capacity of such prioritization was already exceeded when there were four salient objects. Then, participants might randomly choose, say, two of the salient objects for particular attention. As a result, the averaged salience effect in the four salient objects condition was reduced, compared to the two salient objects condition. In either case, it appears the salience effect would eventually disappear when the number of salient objects exceeds a certain level. It would be interesting to conduct

experiments to further investigate the capacity of such a “salience buffer.”

Experiment 2

Participants Twelve college students and graduate students in the Houston medical center area participated in Experiment 2 (four males and eight females, and the average age was 26.3 years with an SD of 4.49 years). Participants were paid for participation.

Procedure The procedure was essentially the same as in Experiment 1. The following were the major differences. The potential targets were 8 dots aligned on a circle at 45° intervals, with the submarine located in the center. When the submarine is aligned upright, these eight dots are on the front, right-front, right, right-back, back, left-back, left, and left-front, respectively (see Figure 4). For the two levels of the number of salient objects, instead of 2 salient objects vs. 4 salient objects, Experiment 2 compared the conditions of 1 salient object vs. 2 salient objects.

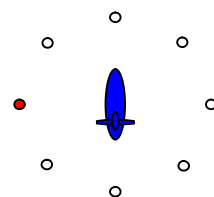


Figure 4

At the beginning of each trial, one blue submarine image and 8 dots (in which 1 or 2 of them were red and the rest were white, on a circle with a diameter approximately of 5.93 cm) were presented simultaneously. All dots were in the same size with a diameter approximately of 0.80 cm. The submarine image, when upright, was approximately 1.98 cm high and 0.88 cm wide. The positions of salient objects were randomly selected (without overlapping with each other). The initial orientation of the submarine was always upright. After flashing 3 times, the submarine started to rotate around the center of the circle. The rotation speed was constant for all trials, which was approximately 0.033° per ms (approximately 2763ms for every 90°). When the submarine reached a certain orientation, it would stop and at the same time one of the eight dots would flash. The rotating distance was determined by the trial settings on the submarine orientation, with a minimum of 45° and a maximum of 360°. Among 256 trials, each 32 trials had the same rotating angle ranging from 45° to 360° in the step of 45°. The order of the trials was randomly shuffled before presentation.

Results The mean RT for the 12 participants was 1772.7 ms with a standard deviation of 663.54ms. The mean accuracy rate was 94.7% with a standard deviation of 6.13%. RT as a function of the target direction is shown in Figure 5, with RT broken down by two salience levels. (RT as a function of the submarine orientation showed the same overlapping pattern. The figure is omitted here to save space.)

The most obvious observation in Figure 5 is the absence of the salience effect: RT for the salient objects was almost identical to that for the non-salient objects. Overall, there was little difference between RT for salient objects and RT for non-salient objects (mean difference = 18.4 ms, $F_{1, 11} = 0.841$, $p = .379$). Moreover, both the main effect of NOS and the interaction of salience and NOS were not significant ($F_{1, 11} = 0.436$, $p = .522$; $F_{1, 11} = 4.190$, $p = .065$, respectively). Though statistically it is impossible to prove the null hypothesis (i.e., the salience effect did not exist), compared to the magnitude of the salience effect observed in Experiment 1, we are confident that the salience effect was at least largely reduced in Experiment 2.

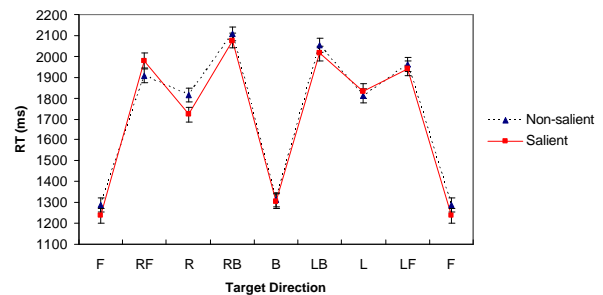


Figure 5. Experiment 2, RT as a function of target direction

Another interesting finding was that RT in Experiment 2 was much slower than that in Experiment 1 for all target directions and submarine orientations. (Figure 6 shows the comparison between all three experiments.) The average difference in RT between Experiment 1 and Experiment 2 was 525.3ms. We suspect that the absence of a stable frame of reference played a major role. Compared to Experiment 1, the major difference in Experiment 2 was that the submarine was rotating constantly before the target was presented. As a result, no stable frame of reference was provided in terms of a fixed submarine orientation. In such a situation, there were two possible strategies of establishing and maintaining a frame of reference. One was that participants could first establish a frame of reference as the submarine was initially presented, then update (i.e., rotate) that frame of reference along with the submarine as it rotated. The other was that participants just waited until the submarine stopped then re-established a frame of reference. We had two reasons to believe that the second strategy was preferred and actually utilized by participants. First, it would take much less effort to re-establish a frame of reference when the submarine stopped rotating, than to maintain a frame of reference by constantly updating it with the rotating submarine. In extreme cases, the submarine would have rotated 360° before it stopped. It would make little sense to update the frame of reference if it would return to its initial position. Second, if the first strategy was actually applied and our participants indeed were updating a frame of reference along with the rotating submarine, Experiment 2 would have had similar RTs as in Experiment 1.

Nevertheless, one may raise the question whether RTs in Experiment 1 and Experiment 2 were directly comparable

since there were confounding factors such as the size of the stimuli and the difference between translation and rotation. For example, it was found that imagined rotation was more difficult than imagined translation (e.g., Presson & Montello, 1994). Due to this consideration, we conducted Experiment 3 with these factors controlled.

Experiment 3

Participants Twelve college students and graduate students in the Houston medical center area participated in Experiment 1 (four males and eight females, and the averaged age was 27.7 years with an SD of 5.55 years). Participants were paid for participation.

Procedure The procedure and device was essentially the same as in Experiment 2. The only difference was that in Experiment 3, the eight surrounding dots were rotating simultaneously while the submarine remained still. Other factors such as the image sizes, the arrangement of the display, and the relative rotation speed, remained the same. The initial orientation of the submarine was randomly selected as one of eight possible orientations. After flashing the submarine three times, the surrounding dots started to rotate around the center of the circle. When they reached a certain location (determined by the trial settings), they would stop and at the same time one of the eight dots would flash.

Results The mean RT for the 12 participants was 1373.1 ms with a standard deviation of 401.68ms. The mean accuracy rate was 93.8% with a standard deviation of 4.52%.

Similar to in Experiments 1 and 2, we observed significant effects of target direction and submarine orientation in Experiment 3 ($F_{7, 77} = 31.590, p < .001$, estimated effect size = .742; $F_{7, 77} = 41.075, p < .001$, estimated effect size = .789, respectively). Similar to Experiment 1, we observed a significant salience effect. Through all target directions and submarine orientations, responses to salient objects were faster than that to non-salient objects. The average difference in RT for salient objects and non-salient objects was 88.8ms, which was statistically significant ($F_{1, 11} = 16.546, p < 0.01$, estimated effect size = .601). (RT as a function of the target direction and a function of the submarine orientation showed the similar split patterns as in Figures 2 and 3. The figures are not shown here.) The salience effect appeared to be very stable across all target directions and submarine orientations: both interactions (salience by target direction, and salience by submarine orientation) were not significant ($F_{7, 77} = 1.123, p = .358$; and $F_{7, 77} = 0.999, p = .439$, respectively).

The number of salient objects (NOS) showed significant effect on RT. On average, RT was faster when NOS = 1 than when NOS = 2 (mean difference = 79.4 ms, $F_{1, 11} = 32.588, p < .001$, estimated effect size = .748). The interaction between NOS and salience was statistically significant ($F_{1, 11} = 42.025, p < .001$, estimated effect size = .793). As a result, it appeared that NOS had little effect on RT when the target was a non-salient object (1415.8 ms when NOS = 1, compared to 1419.2 ms when NOS = 2), but the effect was considerably large when the target was a

salient object (1251.1 ms when NOS = 1, compared to 1406.4 ms when NOS = 2, mean difference = 155.3 ms). In addition, the salience effect here was larger when there was only one salient object (1415.8 ms compared to 1251.1 ms, with a difference of 164.7 ms), but essentially disappeared when there were two salient objects (1419.2 ms compared to 1406.4 ms, with a difference of 12.8 ms). The diminished salience effect could be due to participants' limited capacity in prioritizing salient objects, or due to the conflicting relations between the two target objects and the orienting submarine (for example, the two salient objects could be on the opposite sides of the submarine). We will leave this question to future investigations.

On average, RT in Experiment 3 was faster than in Experiment 2 (average difference was 399.6ms), but still slower than in Experiment 1 (average difference was 125.7ms) (see Figure 6). This observation confirmed the previous hypothesis that rotation was indeed more difficult than translation. However, it also confirmed the hypothesis that faster reaction times can be produced by a relatively stable frame of reference.

General Discussion

We summarize the general findings in the present study by comparing all three experiments. The experiments had similar task instructions (direction pointing by paying specific attentions to the salient objects), but differed mainly in the forms of relative movements between the orienting object and the target objects. By manipulating the relative movement, we obtained different response times. Figure 6 shows the comparison.

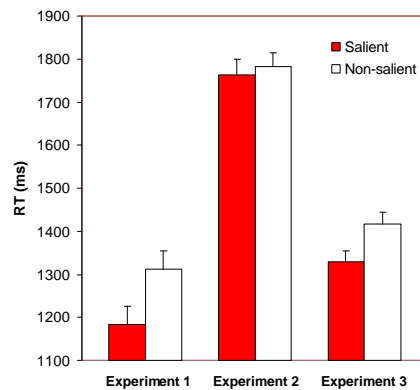


Figure 6. Comparison of RT among three experiments

From a computational point of view, updating of the object-to-object relations in intrinsic frame of reference depends mainly upon two factors: a frame of reference, and a potential target. The different reaction times in the three experiments suggest that a stable frame of reference is critical when the object-to-object relations are to be updated. When the orienting object was rotating, it appeared that the intrinsic frame of reference based on that object was not continuously updated: responses tended to take longer as if a frame of reference had to be re-established. Previous

studies have suggested that egocentric self-to-object spatial relations are updated continuously as people move through an environment (e.g., Sholl & Nolin, 1997; R. Wang, 1999). Our results indicate that maintaining an intrinsic frame of reference is not automatic. The difference might be due to the fact that an egocentric system is relatively easier to be maintained.

Furthermore, we found that given a relatively stable frame of reference, responses for salient objects were significantly faster than those for non-salient objects (Experiments 1 and 3). In addition, the salience effect was largely reduced when a fixed frame of reference was removed (Experiment 2), and re-appeared when a fixed frame of reference was provided (Experiment 3). This observation confirmed our hypothesis that updating of spatial relations can take place dynamically with different priorities when a relatively stable frame of reference is maintained.

Responses to both salient objects and non-salient objects manifested the same orientation dependence in all three experiments, similar to the orientation dependence found in the experiments where egocentric systems were used (e.g., Hintzman, et al.). This similarity might provide an interesting link between the egocentric systems and intrinsic systems. Either participants were imposing an egocentric frame of reference on an external object (e.g., imagine themselves on the orienting submarine), or, as suggested by McNamara (2003), people could in effect treat their bodies as just another object in the space.

Overall, the present study identified several properties of spatial updating in intrinsic frames of reference. In the real world situations, the surrounding environment is constantly changing and people have to adaptively and efficiently prioritize and organize necessary spatial information. Therefore, salient spatial entities, determined by both behavioral and perceptual significance, would receive higher priorities in processing and updating. Furthermore, the current study supports the general claim that multiple reference systems can co-exist in the brain and in the mind to represent space, with each supporting a different class of spatial tasks (H. Wang, Johnson, and Zhang, 2001). For example, while egocentric systems (body-centered) are more convenient for directly supporting motor actions, allocentric systems are more important for representing object-to-object relations in the environment. When a stable allocentric frame of reference is not available, the spatial information will have to be inferred from egocentric information.

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