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## **V - Does mental simulation of following a path improve navigation performance without vision?**

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## **Abstract**

We recorded the paths of subjects who walked along a memorized hexagonal route without vision, and studied the impact of previous mental simulation of this activity on how well the path could be reproduced from memory. We compared two kinds of mental simulation to actual physical practice, rest, or simple memorization of the path. The results indicated that mental simulation led to better reproduction of the global shape of a path than rest, and in fact mental simulation was as effective as actual physical practice. However, this result occurred only for "simple shapes" when the lengths of the sides of the path were kept constant. Nevertheless, this level of performance was not reached when the complexity of the shape was increased by altering the lengths of sides, even when keeping constant the angles between consecutive sides. This finding indicates that the internal representation of space depends on geometric properties of the environment in which the subjects operate. Mental simulation appears to affect both a map-like and route-like representation of the environment.

Theme: Neural basis of behavior

Topic: Cognition

Keywords: Locomotion - Navigation - Geometry - Mental imagery

## *V -1. Introduction*

Mental practice occurs when one imagines performing a motor skill without making overt movements. Such practice has been found to enhance actual performance (Feltz & Landers, 1983; Jones et al., 1997 for reviews). A wide variety of motor tasks, ranging from increasing muscular strength (Yue et al., 1992) to improving accuracy in tasks such as basketball throwing (Savoy & Beitel, 1996) can benefit from mental practice. In general mental practice is more effective than no practice, but not as effective as physical practice. The mechanisms underlying mental practice are of interest both from an applied perspective (such as in motor learning or rehabilitation) and from a theoretical perspective; indeed, the mere fact that mental practice is effective has implications for how the information used in actual performance is stored and used (Jeannerod, 1994 for a review; Melvill Jones & Berthoz, 1985). The fact that mental practice affects actual performance is consistent with well-documented effects of top-down processing. For example, mental effort can contribute to adaptive modification of vestibulo-ocular reflexes during prism wearing; these modifications may be associated with perceptual changes, suggesting that top-down processing can affect even such low-level events (Melvill Jones, Berthoz, & Segal, 1984; Melvill Jones et al., 1985).

Remarkably little is known about whether mental practice can effectively enhance performance during navigation. In this case, subjects are mentally simulating what they would do in the corresponding physical situation; thus, "mental simulation" is the use of imagery—motor and visual—to rehearse or anticipate navigating along a particular path. Mental simulation is a reasonably direct way to manipulate the internal representation and thereby alter its characteristics. This is a particularly interesting domain because it affords an opportunity to study the mechanisms underlying both mental practice and navigation itself.

The present study thus has two overarching goals. First, we wanted to demonstrate that mental simulation can affect the accuracy of walking along a path on the basis of information stored in memory. It is likely that the properties of the internal representation of space can be accessed and even modified by mental imagery. Visual mental images share common properties with the actual objects that they represent; indeed, about two-thirds of the same brain areas are activated during visual imagery and visual perception (Kosslyn, Thompson, & Alpert, 1997). Moreover, Decety (1989) has shown that the timing of mentally represented actions is very close to the timing of the corresponding actual movements. However, this

process, even if rooted in common neural substrates between imagined and executed actions (Roland et al., 1980), should be capable of being modulated. Indeed, interactions may occur between visual and motor images (Wexler et al., 1998), and many studies have shown that mechanical or biomechanical constraints on movement are taken into account when we form mental images. When the movement is very highly constrained or even biomechanically impossible, the timing of the imagined movement deviates from the timing of the actual movement—as if the default tendency of the central nervous system is to simulate natural movements (Parsons, 1994; Parsons, 1987). In the navigation domain, one might expect that the use of mental images could improve the ability to walk down a path (Vieilledent et al., 1996).

It remains unclear whether mental simulation occurs only in the head, or is more effective when one actually makes movements—even "abbreviated movements" that arise from executing "movement programs". During imagined movements, researchers have shown that low amplitude muscular patterns appear in the muscles along with small segmental movements. The seminal studies of Jacobson (1932) documented that mental training is accompanied by electromyographic activity (EMG) in a muscle at rest if this muscle is typically involved in the corresponding actual movement. Wehner et al. (1984) found a spectral distribution of the EMG signal in the biceps brachii that was very similar to the signal recorded during the actual movement. This peripheral EMG activity would be sufficient to send kinesthetic information to the CNS, which could evoke a motor image of the actual movement. In our study, "abbreviated movements" do not specifically refer to the EMG activity but rather, at a more macroscopic level, to the small movements accompanying mental simulation. Thus, in the present study we explicitly compare mental simulation both with and without "abbreviated movements" to other forms of learning a path.

Our second general goal was to use mental simulation to gain insight into how pathways are represented in memory. During navigation, sensory inputs play an important role in spatial perception, learning, and memory (Loomis et al., 1993). In particular, vision allows animals to guide their locomotion along particular paths and provides information about the general layout of the surroundings. Although locomotion usually seems effortless, the process is remarkably complex — particularly when direct perception of the surroundings is not available. In this case, one is following a remembered path and must not only encode different pieces of information about the surrounding space as well as the state of the displaced body and its actual position in space, but also must compare this information to representations of the potential paths to a goal (Able, 1989; Gallistel, 1990).

Information in memory may guide navigation in two major ways. On the one hand, situations in which subjects find their way in the absence of external cues may rely on the computation of their position in space with respect to their starting point (Berthoz et al., 1995; Marlinsky, 1999b; Marlinsky, 1999a). In this step-by-step process of "path integration", vestibular linear and angular acceleration signals are integrated to provide an estimate of the current position based on an estimate of the previous one. This mechanism, clearly involved in navigation without vision, relies on measures of the variations of one's own internal state and of the configuration of the sensory receptors (Etienne et al., 1999; Mittelstaedt et al., 1982; Israël et al., 1997; Mittelstaedt et al., 1991).

On the other hand, locomotion without external cues may also require the use of "mental models," internal representations of the geometry of a space, to prevent subjects from experiencing the sensation of being lost or even momentary disoriented. These mental models rely on one's "point of view" (Etienne et al., 1996); in this case, salient points of the environment are identified and used as landmarks in route or survey representations of the environment (Klatzky et al., 1990). We hypothesize that such internal representations can be augmented not only by direct observation, but also by "mental simulation" — by imagining that one is moving through the environment. Indeed, during navigation subjects may use complex combinations of translation and rotation displacements to fit the shape of the desired path; navigation may be guided by an implicit or explicit geometric internal model that one tries to reproduce. In order to do so, subjects would build up a representation that in turn guides their navigation behavior in the environment.

Recent results (Takei et al., 1997; Berthoz et al., 1999) document a dissociation between the coding of distance and direction during blind locomotion. These findings suggest that a polar coding of space is used to guide navigation, at least in some circumstances. One may ask how this type of coding is compatible with a global map-like representation of the 2D trajectory. It is possible that both a route-like and a map-like representation of the path are used in navigation (Mellet et al., 2000). If a route representation is present, then mental practice could have separable effects on representations of distance versus angles between segments of a path; the route representation would preserve the distinction between these two sorts of information. In contrast, if a map-like representation is used, then the overall shape of a path might be affected by mental simulation, not distances and angles separately. It is also possible that both the global shape of a path and specific aspects of routes are simultaneously represented, as suggested by the idea that two distinct types of representations are present.

To study the characteristics of the information stored in memory that guides locomotion, we study navigation without visual feedback. If people see the path to be followed or see the landmarks to be reached before beginning a navigation task without vision, a stored representation of the path can subsequently be used to guide navigation. But the representation of space may be subject to distortions that do not preserve the metric and topologic relationships of its different parts (Giraudo et al., 1994). This notion is in accordance with the "cognitive collage" metaphor, which highlights the breakdown of space into several sub-spaces, each with their own geometrical properties (Tversky, 1993).

The present study is a systematic investigation of the contribution of mental simulation to the acquisition of spatial knowledge. In particular, we address the following questions: 1) Is mental simulation more efficient than rest in helping one to reproduce a path during navigation without vision? 2) Is mental simulation poorer than learning a path via actual movement? 3) Is memorizing the appearance of a path and explicitly trying to reproduce it better than actual movement? 4) Is mental simulation more effective for promoting learning than simply reproducing a memorized path? 5) Finally, what is the role played by the geometry of the path to be followed? We investigate the influence of modifying the length of particular segments versus the angles between adjacent segments. By varying paths in these ways, we sought to discover whether mental simulation or the other learning techniques favor one sort of information over the other—or whether neither sort per se is stored more effectively, but instead a "global shape" configuration is stored.



## ***V -2. Material and methods***

### **V -2.1.Subjects**

Thirty two male subjects ages 22 to 55 years (mean = 35.8, SD = 10.1) volunteered to participate in this experiment. They were naive with respect to the purposes of the study and had not previously participated in experiments on locomotor path reproduction or mental imagery. None of them reported sensory or motor problems. Each subject was randomly assigned to one of the five experimental groups. Data were excluded from two subjects whose performance was abnormal; that is, these two subjects had very long walking durations, and often walked very far outside the calibrated space. Data from two other subjects were not used because of problems during computerized acquisition. In the end, we analyzed the data from 28 subjects, distributed in the different groups as follows: G1, 5 subjects; G2, 6 subjects; G3, 5 subjects; G4, 6 subjects and G5, 6 subjects.

### **V -2.2.Task and procedure**

We designed three different six-sided paths with wooden beams 7 cm wide and 3.5 cm high (see Figure V-1). All paths were 12.15 m long, but differently shaped. The first one was a perfectly regular hexagon; each side was 2.03 m long, and the angle between every pair of successive sides was 60°. This regular hexagon will be referred to as RH. The other two paths were modified versions of RH. One of them preserved the angles (PA), but not the lengths of the sides; the angle between two successive sides was always 60°, but their length alternated between 1.55 m and 2.5 m. Finally, the third path preserved the distances (PD) of each side (2.03 m), but not the angles (48.5° and 83°).

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Insert Figure V-1 and Figure V-2 about here

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All subjects began by observing the path, and then learned it according to a specific method (as will be described shortly), and then walked with the aim of reproducing the shape of the path (see Figure V-2). In order to prevent them from perceiving any information about their position in the environment, all subjects were equipped with black goggles and a personal stereo that delivered white noise while they traced the path. All subjects performed

eight trials for each path, with the paths being presented in a counterbalanced order within each group.

#### Observation phase

Subjects stood in an upright posture on a 0.8 \* 0.8 m square platform located at the departure point. They saw the path for the first time and received the instructions about the task. Remaining on the platform, they were given two minutes to observe the path and memorize the positions of the departure point, the corners, and the arrival point, knowing that they would have to orient themselves and walk to each successive corner until they reached the arrival point.

#### Learning phase

This phase always followed the observation phase and was different for each of the five groups. However it lasted five minutes in all cases.

*Group 1, Simulation without movement:* Seated on a chair located at the departure point and facing the first corner, subjects were asked to mentally simulate walking along the path. They were to begin their mental simulation at the departure point, and end at the arrival point. The subjects were told to take a direct path between each pair of successive corners. The subjects were told to indicate when they began the mental simulation, each time they turned a corner during this simulation, and when they reached the arrival point; they made these responses by pressing a key on a remote control that they held with both hands in front of their chest. This device was synchronized with a motion capture device (see below). The same timing procedure was also used by the subjects in Groups 2, 3 and 5. The orientation at the arrival point was the same as the orientation of the last side of the path (corner 5 - arrival point).

*Group 2, Simulation with movement:* As they did during the observation phase, subjects in this group stood in an upright posture and were oriented toward the first corner. They were asked to step in place, taking a "virtual walk", and to orient themselves toward the successive corners. They were to produce rotations around their own longitudinal axis but no translation; they moved in place. At the end of each trial the subjects kept their goggles and headphones on, and were passively turned by an experimenter in randomized sequences until they reached the initial orientation. Before beginning the next trial, the subjects were allowed to glance briefly at the first corner and accurately adjust their orientation.

*Group 3, Constrained movement:* Subjects in this group learned the paths by actually walking on the wooden beams, from the departure to the arrival point with eyes opened.

*Group 4, Rest:* Subjects in this group sat on a chair located at the departure point, and were oriented toward the first corner. Like the other subjects, they wore black goggles and a personal stereo delivering white noise, but unlike the others they did not simulate anything. The subjects of this group rested 5 minutes. This duration corresponds to the average overall duration of the learning phase of the four other groups.

*Group 5, Memorized reproduction:* For this group, the beams were removed from the ground and the subjects were told to reproduce the path by walking on a flat floor, which they did just after the observation phase. After each trial, an experimenter passively led the subjects to the departure position, following random paths (to minimize the cues that would allow the subjects to receive feedback on their performance or to infer their position in the environment). Just before the following trial, subjects were allowed to take off the goggles and adjust their position and orientation.

#### Walking phase

We were primarily interested in the effects of the different learning procedures on how well subjects subsequently reproduced the path from memory. We assessed their memory by asking them to walk along the path on the flat floor. This phase always took place after the observation and learning phases. Subjects performed eight actual walking trials with goggles and white noise on, and indicated their starting, direction changes, and arrival by mean of the remote control. In fact, these trials corresponded exactly to the learning trials of the Group 5.

By observing the shape of the walked trajectories for the three types of paths, RH, PA and PD, we sought to discover what sort of information was practiced during the different learning conditions. In particular we wanted to know what geometrical variations of the shapes the subjects could process during the learning phase. Our hypothesis was that if subjects could take into account the variations in distances, the performance for PA and RH should be equivalent; and if subjects learned the variations of angles, the performance for PD and RH should be equivalent.

In summary, our procedure had three distinct phases (observation, learning, and walking), three paths (RH, PA and PD), and five learning conditions (Groups 1 - 5). We took eight measurements for each subject and path during both learning and blindfolded walking phases. Thus, each subject performed  $2 \text{ (phases)} * 3 \text{ (paths)} * 8 \text{ (measurements)} = 48$  trials.

### V -2.3.Data acquisition and analysis

We calibrated a 10 (width) \* 10 (length) \* 2.5 (high) m<sup>3</sup> volume with a seven-camera, infrared optoelectronic motion capture device (Vicon 370, Oxford Metrics Ltd). This system interfaced with an analog-to-digital converter, and allowed us both to record the 3D position of a passive lumino reflexive marker and localize analog signals sent by the subject by means of a remote control. The marker was located on the center of a helmet worn by the subject. The marker was precisely aligned with the body longitudinal axis and provided the position of the subject. In the present study, we focused on the horizontal components of this position (xy plane). The sample rate was 60 frames per second and the mean spatial error was  $0.005 \pm 0.001$  m. Raw position data were interpolated with a polynomial algorithm. Our method consisted of filling any gaps in data collection if the amount of missing data was smaller than 10 consecutive samples (160 msec.). The interpolation procedure was applied with Vicon Workstation software (version 3.7), which de facto relied on a polynomial algorithm. Those files with more than 10 consecutive remaining missing samples, however, were excluded from further analyses. Interpolated data were then filtered with a Butterworth low pass, fourth-order, recursive filter, using a 5 Hz cutoff frequency (Winter, Sidwall, & Hobson, 1974) in order to remove all high frequency components from the position signals that could be generated independently of the movement of the subjects themselves.

To compare the correct shape of the path with the shape of the trajectories the subjects actually took, we considered the seven horizontal position samples where subjects pressed the remote control during each trial of the walking phase. These positions corresponded to the imagined positions of the departure, corners, and arrival points; linked together, these positions specified the shape of the imagined path. We performed a two-dimensional regression analysis that computed a correlation coefficient ( $r$ ) between the set of actual vertices and the set of imagined corresponding positions. Moreover, we were able to compute an indicator of the mean discrepancy (root mean square error, RMSE) between the two shapes being compared. The RMSE provided an estimate of the distance between the correct positions of the points and the equivalent points of the subjects' trajectories. This measure is based on three Euclidian transformations : i) a translation to fit the centers of gravity of the two sets of points; ii) a rotation; and, iii) a scale factor to minimize the mean distance between the points according to the least squares method. This bi-dimensional regression calculation is directly in line with the one used by Kosslyn et al. (1974) and has been extensively described (Giraudo et al., 1994). The basic principle is to compare the discrepancy between two spatial

configurations of  $n$  homologous points distributed in the 2D space (Tobler, 1977; Tobler, 1976; Tobler, 1978). For this, we define a first configuration, named A, with the set of coordinates  $(X_i, Y_i)$  of the actual corners of the hexagon and a second one, named I, with the set of coordinates of the imagined corners  $(U_i, V_i)$ . The discrepancy between the two configurations (actual A and imagined I) can be represented by the vector AI, specifically the vector  $(X_i, Y_i), (U_i, V_i)$ . The problem lies in determining the best fit of the actual configuration A on the imagined configuration I. Here, as in one-dimensional spaces, the best fitting function minimizes the difference between the two configurations. To achieve this goal, we determine  $f$ , a function of A, that adjusts A to I as close as possible. The remaining overall discrepancy between the A and I configurations is the mean distance between the points of A and the corresponding points of I, which is a measure of global error and is quantified by mean of the root mean square error (RMSE). Thus, there is no linear relationship between the mean discrepancy for the overall configuration and the local discrepancy for each point, even if these two measures are related one to each other in the sense that an increase in the mean RMSE may be induced by an increase in local discrepancies.

Repeated measurements analysis of variance (ANOVA) were performed to compare the geometric properties of the walked paths between groups (5), shapes of the model (3), and trials (8).

### V -3. Results

We focused on the paths reproduced during the walking phase. These paths are shapes with six sides, for which lengths and orientations can vary between groups (Figure V-3). Subjects tended to reproduce well the actual path when initially walking along the first side, but began to deviate when they reoriented their bodies and walked along the following sides. This behavior may indicate discrepancies between the actual shape of the path and the mental model constructed by the subjects.

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insert Figure V-3 about here  
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To compute and compare *means of correlation coefficients* Fisher's z-transformation was used to improve normality. Coefficients are given after transformation back to the original scale. The values of the pooled correlation coefficients  $r$  for all stimulus paths are displayed in Figure V-4A. They are  $0.86 \pm 0.20$  for RH,  $0.90 \pm 0.15$  for PA and  $0.86 \pm 0.16$  for PD. These results show that the reproduced shape remains very close to the shape of the actual path for all groups and paths. Indeed, there was no difference between groups ( $F(4,20) = .48$ ;  $p > .05$ ) or paths ( $F(2,40) = 1.16$ ;  $p > .05$ ), and the interaction of these two factors failed even to approach significance ( $F(8,40) = .87$ ;  $p > .05$ ). Moreover, the correlation coefficient remained unchanged from the first to the last trial ( $F(7,140) = .64$ ,  $p > .05$ ).

However, considering all the trajectories produced during the walking phase, we note that the RMSE values varied from  $8.4 \pm 1.4$  cm for G3 to  $10.3 \pm 1.9$  cm for G5 (see Figure V-4B). These values were significantly different ( $F(4, 20) = 2.96$ ,  $p < .05$ ), but there were no significant effects of the shape of the path reproduced by the subjects ( $F(2,40) = 1.64$ ,  $p > .05$ ) and no significant effect of the trial ( $F(7,140) = .64$ ,  $p > .05$ ). There was, however, an interaction between shape and trial ( $F(14,280) = 1.75$ ,  $p < .05$ ) mainly arising from an interaction between PA and RH ( $F(7,140) = 2.82$ ,  $p < .05$ ). This finding seemed to reflect an increasing tendency of the RMSE for RH accompanied by a decreasing for PA from trial 1 to trial 8.

When comparing the groups, we found that the RMSE did not differ between the two first groups, G1 and G2, when pooling the shapes together ( $F(1,20) = .19$ ,  $p > .05$ ) or considering them separately ( $F(1,21) = .00$ ,  $p > .05$  for RH ;  $F(1,23) = .65$ ,  $p > .05$  for PD and

$F(1,22) = .11, p > .05$  for PA). Therefore we pooled data from these two groups in the subsequent analysis. Planned comparisons also revealed that performance improved with simulation (G1-G2) during the learning phase compared to rest (G4) for RH ( $F(1,21) = 4.46, p < .05$ ) and PD ( $F(1,23) = 4.41, p < .05$ ). However, this result did not occur with the PA path ( $F(1,22) = .79, p > .05$ ). Moreover, G1-G2 and G3 had comparable performance (with  $F(1,21) = .31, p > .05$  for RH ;  $F(1,23) = .16, p > .05$  for PD and  $F(1,22) = 1.27, p > .05$  for PA). In addition, the same comparisons performed between G1-G2 and G5 revealed that participants in G1-G2 were more accurate than those in G5 for RH ( $F(1,21) = 6.50, p < .05$ ) and PD ( $F(1,23) = 9.26, p < .001$ ) but we did not observe such a difference for PA ( $F(1,22) = .41, p > .05$ ). Finally, G4 and G5 performed comparably ( $F(1,20) = .19, p > .05$ ), and did so for each shape with  $F(1,21) = .40, p > .05, F(1,23) = 2.71, p > .05$  and  $F(1,22) = .06, p > .05$  respectively for RH, PD and PA.

Furthermore, we found a significant difference ( $F(1, 20) = 10.17, p < .01$ ) between the values from the three first groups (G1-G3) versus those from the two last groups (G4 and G5). This result indicates first that subjects who simulated locomotion during the learning phase (G1 and G2) had better shape reproduction performance than subjects who rested (G4), and second that their performance is equivalent to that of subjects who learned by actually walking on the beams. However, planned comparisons showed that this segmentation of the groups in two distinct categories (G1-G3 versus G4-G5) is only evident when the shape to be reproduced did not vary the lengths of the sides (see Table V-1): we found significant differences for RH ( $F(1, 21) = 11.21, p < .01$ ) and PD ( $F(1,23) = 6.82 p < .05$ ) but not for PA ( $F(1,22) = .92, p > .05$ ).

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insert Figure V-4 and Table V-1 about here  
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We further analyzed the characteristics of each type of transformation in order to probe more deeply into the reasons why the subjects in G1, G2 and G3 more accurately reproduced the path than subjects in G4 and G5.

The analysis of the scale factor values (Figure V-5 C) revealed that the observed differences between G1-G3 and G4-G5 for RMSE did not originate from any positive or negative zooming effect specific to the learning condition ( $F(4,20) = .66 p > .05$ ) or from the shape to be reproduced ( $F(2,40) = 1.56 p > .05$ ). However, the analysis of the translation

values (Figure V-5 A) and the rotation (Figure V-5 B) values did provide two main insights into the causes of the observed difference. First, the distance between the center of gravity of the actual corners and the center of gravity of the imagined corners depends on the learning condition ( $F(4,20) = 6.47$   $p < .01$ ), with systematically higher values for G5 than for the other groups. This result was obtained for RH ( $F(1, 21) = 14.15$ ,  $p < .001$ ) and PD ( $F(1,23) = 28.22$   $p < .001$ ), but not for PA ( $F(1,22) = .92$   $p > .05$ ). Because the scale factor did not significantly differ from one group to another, the present result suggests that the subjects in G5 emphasized detours outside the actual shapes, at least for some parts of the path (Figure V-6). This inference is supported by the direction of the displacement of the center of gravity of the imagined corners with respect the actual ones. Considering the x axis as being the reference direction and the counterclockwise direction as being positive, the mean direction is  $90,97^\circ \pm 42.87^\circ$  for RH,  $96.10^\circ \pm 41.96^\circ$  for PD and  $50.95^\circ \pm 63.44^\circ$  for PA. This means, on the one hand, that the center of gravity tends to move along the y axis for RH and PD -- i.e., the main axis of these two shapes -- and, on the other hand, that for PA it tends to move along an intermediate direction between the two main axis of this shape.

Second, the rotation applied to minimize the distances between actual and imagined corners significantly varied according to the learning condition. The amount of rotation was higher for G4 than for each of the other groups ( $p < .001$ ). This significant difference in the angle of rotation means that subjects in G4 tended to change the main orientation of the imagined path without changing significantly its size and overall position. In other words, the comparable results for the RMSE from G1-G3 were obtained with quantitatively equivalent values for each Euclidian transformation. The observed differences for RMSE between G1-G3 and G4-G5 are due to a discrepancy in at least one of these transformations (translation for G5 and rotation for G4).

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insert Figure V-5 and Figure V-6 about here  
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#### *V -4. Discussion*

In this experiment we manipulated the internal representation of a path by asking subjects to engage in different learning procedures. Let us consider each of the specific questions we asked.

1) Is mental simulation more efficient than rest in helping one to reproduce a path during navigation without vision? The answer is clearly positive, as shown by high values of the correlation coefficient accompanied by low values of RMSE for the first two groups of subjects (G1 and G2). Carrying out a mental simulation allowed subjects to produce a shape closer to the actual path than the shape produced by subjects who rested.

2) Is mental simulation poorer than learning a path via actual movement? The fact that the correlation coefficients are very high and that the RMSE does not significantly differ for the first three groups is evidence that subjects learned the path via mental simulation as well as in the other two conditions. This was not the case for the group of subjects who rested during the learning phase.

3) Is memorizing the appearance of a path and explicitly trying to reproduce it better than actual movement? The comparison of the two groups that produced a walking pattern during the learning phase mainly shows that the mechanical constraints provided by the beams led subjects in G3 to reduce the distances between corners they imagined and the actual corners. Learning may have been more effective when the walk is constrained (G3) than when it is not, but instead is based on the memorized shape of the path to be followed. For the subjects of G5, both the absence of motor constraints generated by the beams and the absence of visual feedback may have contributed to their relatively poor performance.

4) Is mental simulation more effective than reproducing a memorized path? The important role played by mental simulation was confirmed by the comparison of the effects of this learning method to those obtained with memorized reproduction, and our main result showed that the RMSE was lower for the two simulation groups (G1 and G2) than for G5.

We found that mental simulation (with or without movement) led subjects to produce paths that were very similar to the actual paths, on one hand, and to the paths produced by subjects who actually walked during the learning phase in a constrained situation (G3), on the other hand. The fact that two mental simulation learning methods were more efficient than rest or memorized reproduction underscores the importance of imagining locomotion for navigation (Ghaem et al., 1997; Mellet et al., 1995). These two learning methods provided the subjects with a more-or-less distorted internal representation that, nevertheless, specified key

aspects of the path to be followed. On the other hand, rest and memorized reproduction did not improve the representation of the shape of the path.

The key mechanisms used in navigation introduce kinesthetic information into organized temporal sequences (events provided by the subjects themselves) to control movement along a path. We suggest that the simulation used by the subjects not only helped them to encode the movements necessary to walk along the path, but also the shape of this path itself. The internal representation of the path is a composite that includes kinematic and dynamic properties related to the motor functions that underlie both navigation and locomotion.

5) Finally, what is the role played by the geometry of the path to be followed? The results are consistent with the idea that when simulating and walking, subjects used local compensation strategies to preserve the geometrical proportions of the overall path (G1-G3). This finding is consistent with the subjects' using a map-like internal representation. This was not the case for subjects who rested or memorized and immediately walked (G4-G5); when these subjects focused on local reproductions, they lost the global image of the actual path. They did not compensate for local adjustments, probably because their learning method did not allow them to store the overall shape in a map-like representation. Instead, they apparently stored some parts of the path in a route-like representation. Even when some local properties of the path were modified, the subjects in the first three groups could maintain its overall geometrical properties.

We also sought to manipulate the internal representation of the path by modifying the distances or angles of successive segments. In particular, we were interested in determining whether mental simulation could enhance the internal representation even when adjustments to variations in distances (PA) or angles (PD) were needed. Each variation was produced by changing a single parameter, either the side length or the angle between two consecutive sides. For this reason, we never compare PA and PD directly -- they are different both in terms of distance and angle. Essentially, when creating PA and PD, we also modified the symmetry properties of these two variant versions of RH. Because of its three non-orthogonal axes of symmetry (and the absence of orthogonal axis of symmetry), PA is "more complex" than RH and PD, even though RH also has three non-orthogonal axis of symmetry. Moreover, and contrary to their location during the observation phase for RH and PD, the subjects did not observe PA from a location aligned with an axis of symmetry of this particular shape. This might have also increased the complexity of their internal representation of the global image of PA.

The observed differences between the first three groups (G1-G3) and the two last ones (G4-G5) for RH and PD, and the absence of difference for PA, support the idea that the representation of space depends on the geometric properties of the environment in which the subjects operate. This result might be explained by the fact that the learning procedure adopted by the subjects in G1 to G3 led them to build an internal representation of the paths as global shapes. In these cases the subjects based their simulations on the constancy of the distances and, in so doing, were not influenced by the local modifications of the angles. For PA, we suggest that the subjects in the simulation groups failed to reconstruct a global image of the shape. They might have misinterpreted the global layout of the six sides of the paths as well as the increased complexity of this shape by using partial local views, which is consistent with their using a route-like representation at least intermittently.

This line of thought is consistent with the idea that mental simulation contributes to navigation without vision because of the regularity of the translations the subjects perform when walking. In other words, keeping the rotations constant (PA) does not contribute to the benefit subjects receive from mental simulation. Subjects had more difficulty processing the variations in distances (PA) than the variations in angles (PD). In this respect, the RH path preserves both the distances and the rotations.

Nevertheless, we suggest that the subjects in G1, G2 and G3 have better performance because this particular shape is a regular hexagon, and many subjects were probably assuming by default that a hexagon has equal sides and angles when they mentally simulated. In this case the perfect symmetry of the shape allowed the subjects to consider the path as a global shape despite the preservation of the angles. Even if the angles are preserved, the subjects could benefit from the simulation learning. The interactions between the local geometry that is embodied in the internal representation and the position of the subject in space probably obey some non-arbitrary rules (Amorim & Stucchi, 1997). In particular, our results support the hypothesis that in order to produce a locomotor path without visual information about their current position in space, subjects reconstruct this position on the base of a representation of the movement of their own body in space. In this case, the internal representation may share properties of visual mental imagery (Shepard & Metzler, 1971; Cooper & Shepard, 1973; Kosslyn et al., 1978).

However, as shown by the interactions among cognitive tasks and locomotion along complex paths, it remains difficult to demonstrate that the recorded errors originate from a deficit in the cognitive representation of space (Smyth & Waller, 1998). In other words, top-down strategies may be involved when one encodes knowledge about space, but they are

probably associated with multi-sensory information garnered through bottom-up processes. The two kinds of information are melded to produce a single representation. Because the internal representation is based on all sources of information, it is difficult to estimate the relative role played by peripheral signals versus central cartographic information. We are only now beginning to understand the relation between the deformations of the mental representation of space and the geometrical deformations of the navigation space itself. Nevertheless, it appears reasonable to infer that people use both route-like and map-like representations when navigating, and that mental simulation can affect both sorts of representations.

## Figures caption

Figure V-1: Position of the paths used as models for the simulated and actual movements. A: Regular hexagon (RH) where departure / arrival point, corners and direction of locomotion are indicated. B: Preserved Angle hexagon (PA). C: Preserved Distance hexagon (PD).

Figure V-2: Experimental protocol.

Figure V-3: Paths followed. Paths followed by a typical subject of Group 1 (A), Group 3 (B) and Group 5 (C) during the 8 trials of the walking phase for the regular hexagon (RH). The crosses show the imagined corners and their positions can be compared to the position of the corresponding corner of the model.

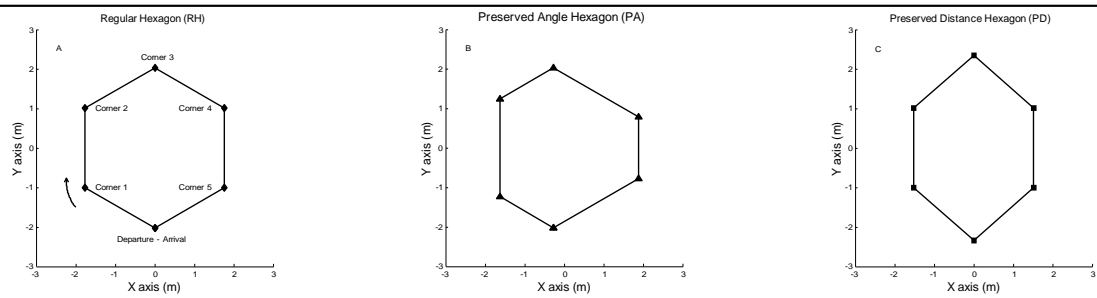
Figure V-4: Comparison of the reproduced paths to the models. Mean and SD of: A)  $r$  and B) RMSE for all paths and each group.

Figure V-5: Parameters of the adjustment between the actual corners and the imagined corners during the walking phase. Mean and SD of the: A) length of the translation, B) amplitude of the rotation and C) scale factor applied to fit the imagined shape of the path to the actual one.

Figure V-6: Paths followed. Paths performed by the subjects of Group 5 for each hexagon during the walking phase. The crosses show the imagined corners and their positions can be compared to the position of the corresponding corner of the model.

## **Table caption**

Table V-1: Mean and SD (cm) of RMSE for each path and group.



**Figure V-1**

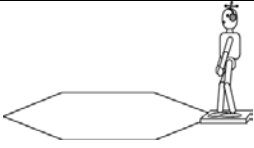
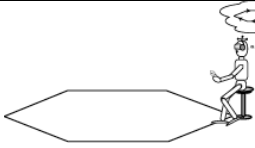
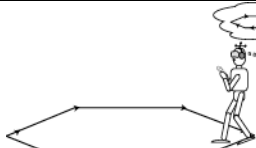
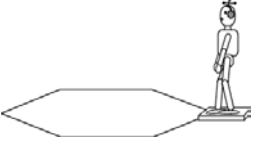
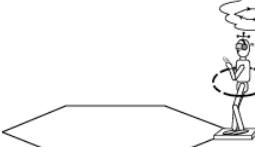
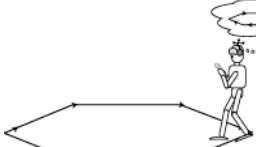
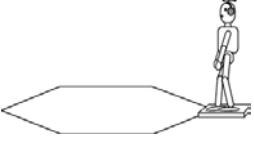

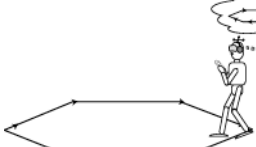
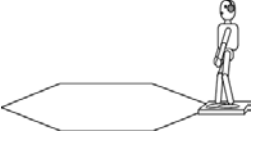
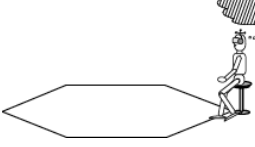
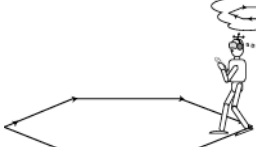
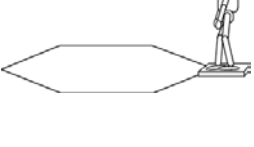
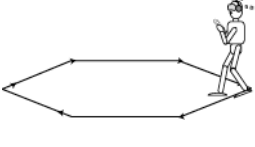
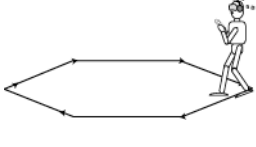
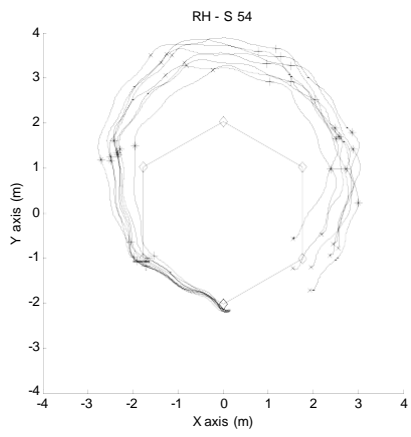
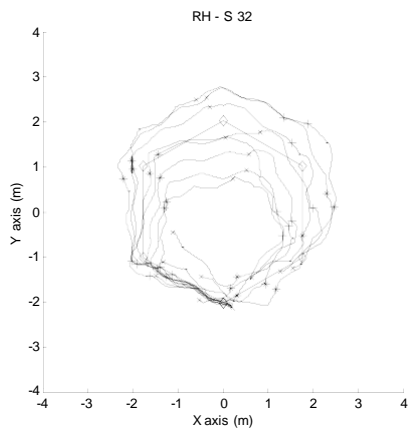
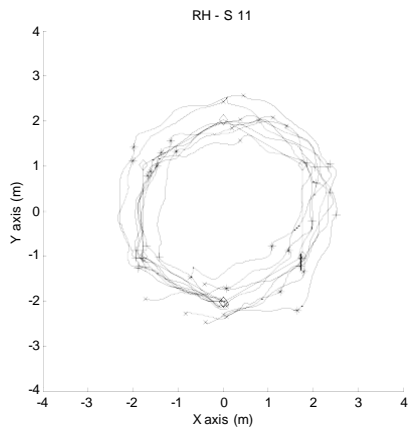
Group	Observation (2 minutes)	Learning (8 trials)	Walking (8 trials)
G1 Simulation without movement			
G2 Simulation with movement			
G3 Constrained Movement			
G4 Rest			
G5 Memorized Reproduction			

Figure V-2





**Figure V-3**

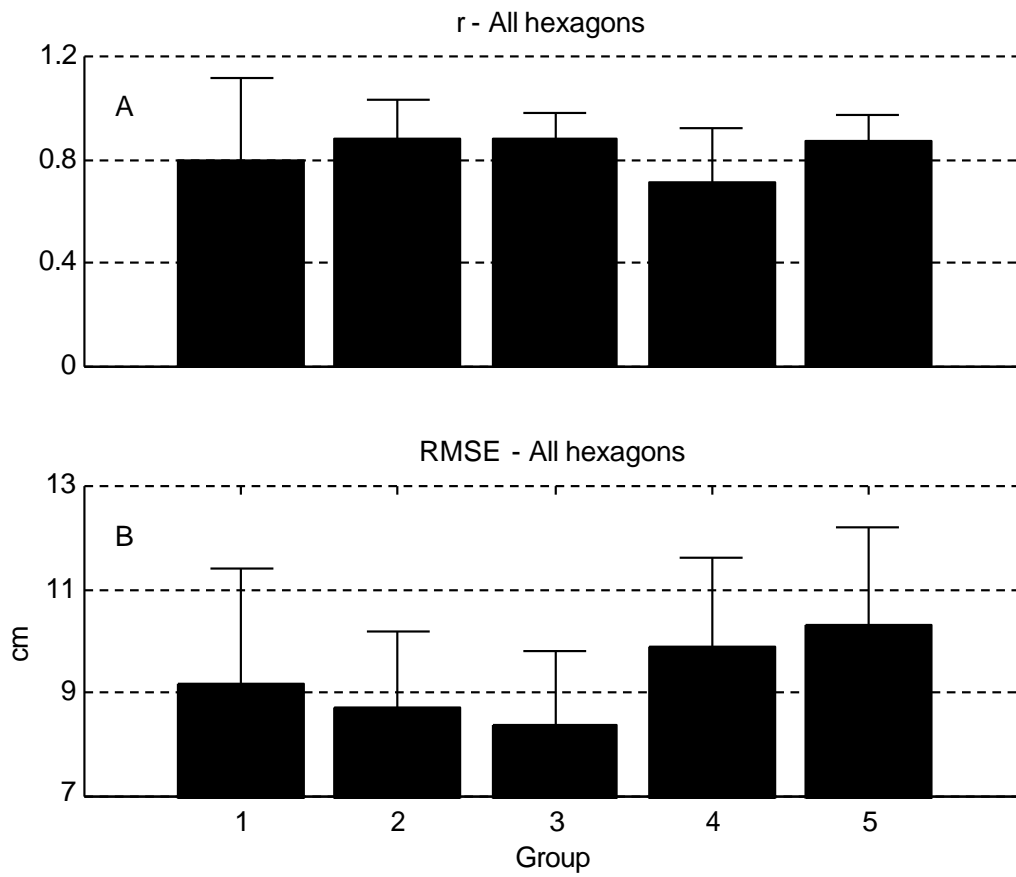


Figure V-4

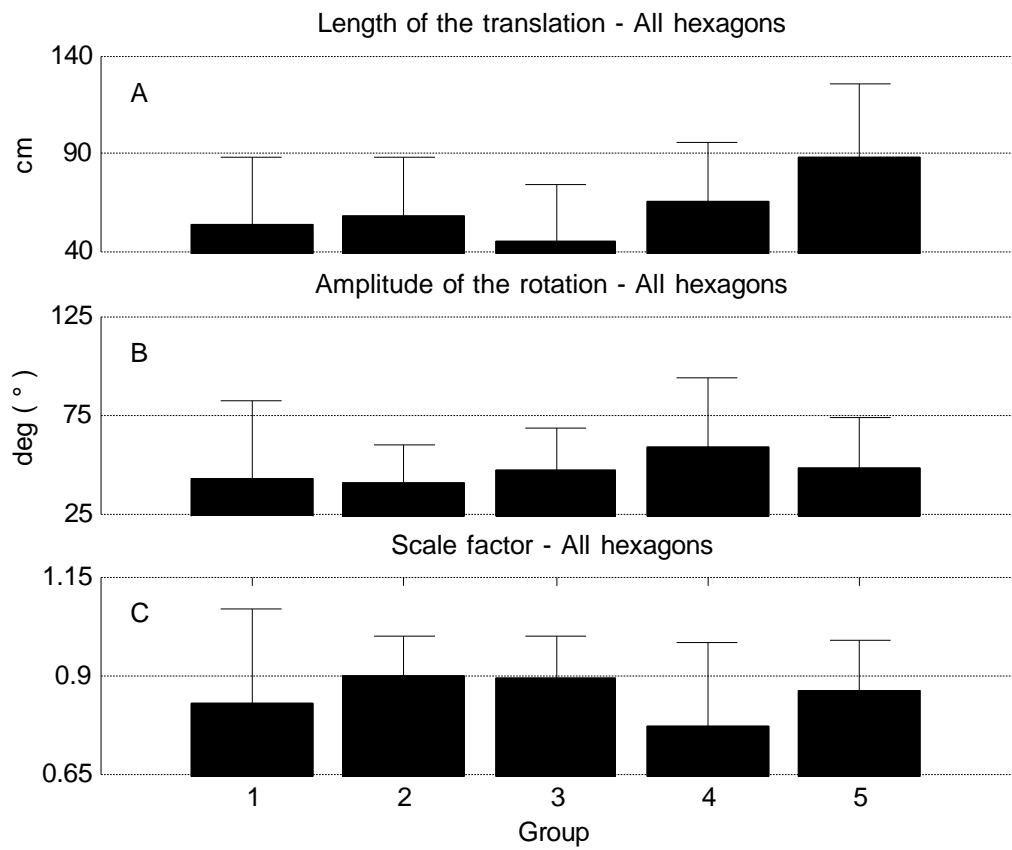


Figure V-5

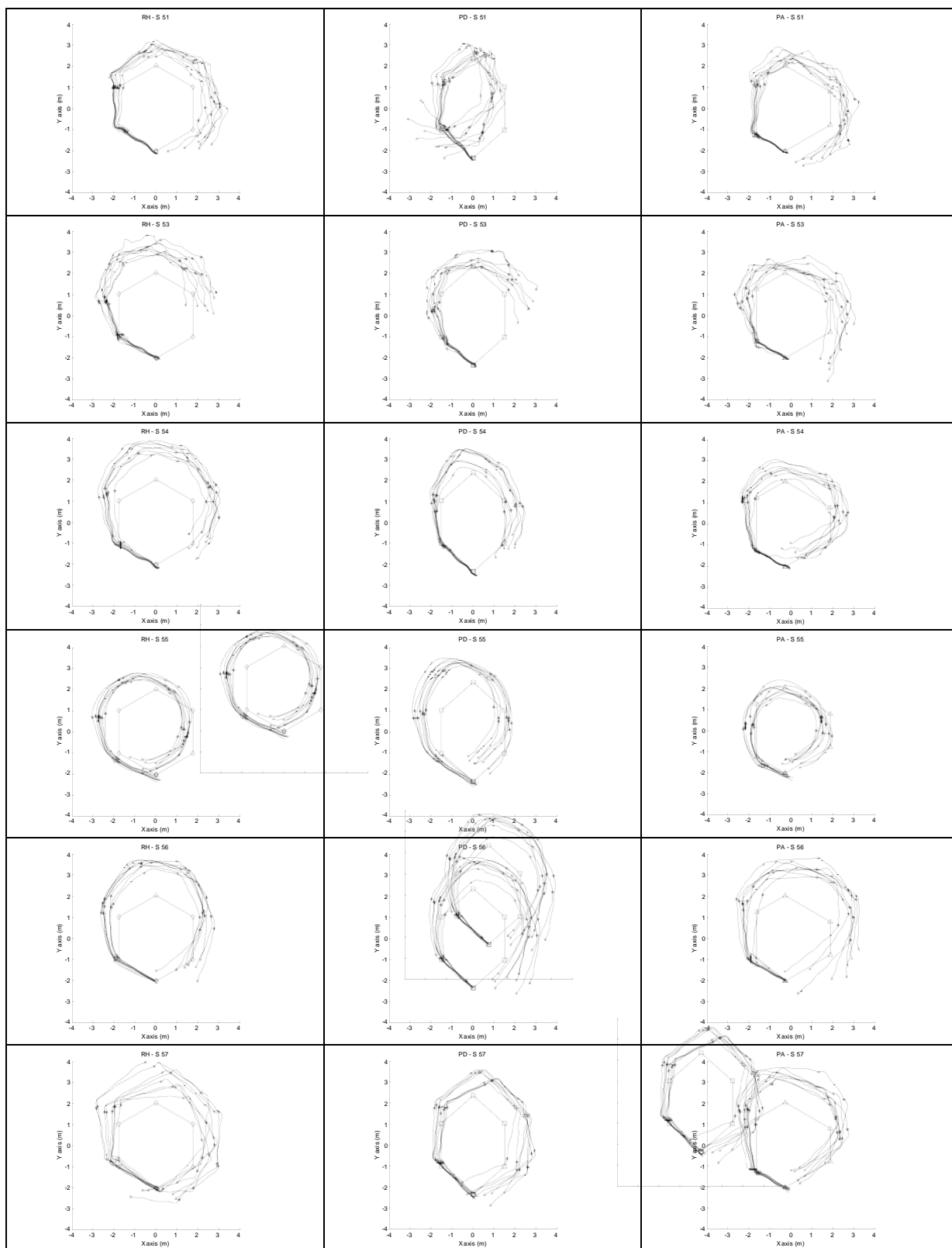


Figure V-6

Group	RH		PA		PD	
	M	SD	M	SD	M	SD
G1	8.9	2.6	9.3	2.4	8.8	1.5
G2	9	1.3	9	1.5	8.2	1.7
G3	8.5	1.4	8.3	1.7	8.8	1.2
G4	10.7	1.4	9.8	1.8	9.3	1.6
G5	10.9	1.9	9.6	1.8	10.4	1.9

**Table V-1**