Romanian Journal of Applied Psychology
2016, Vol. 18, No. 2, 33-39

Selection of spatial reference frames depends on task's demands

Greeshma Sharma[1], Sushil Chandra[1], Vijander Singh[2] & Alok Prakash Mittal [2]

[1]*Bio Medical Engineering Department, Institute of nuclear medicine and Allied sciences (INMAS), DRDO Delhi, India*

[2]*Instrumentation and Control Engineering Department, Netaji Subhas Institute of Technology (NSIT), Delhi, India*

Received 14.09.2016; Received revised 2.12.2016; Accepted 11.12.2016
Available online 30.12.2016

Spatial reference frames (SRF) are the means of representing spatial relations or locations either in an egocentric coordinate system (centred on navigator) or in an allocentric coordinate system (Centred on object). It is necessary to understand when and how spatial representation switches between allocentric and egocentric reference frames in context to spatial tasks. The objective of this study was to explore if the elementary spatial representation does exist, whether it would remain consistent or change under the influence of a task's demand. Also, we explored how the SRF would assist if the environment is enriched with landmarks, having multiple routes for wayfinding. The results showed that the switching of SRF depends not only on the default representation but also on a task's demand. They also demonstrated that participants who were using allocentric representation performed better in the presence of landmarks.

Keywords: Spatial Representation, Spatial Visualization, Spatial Updating, Spatial Orientation, Virtual Reality.

Corresponding author: Greeshma Sharma, Institute of Nuclear Medicine & Allied Sciences, Lucknow Road, Timarpur, Delhi - 110 054
E-mail: greeshmacct@gmail.com

Introduction

Reference frame (RF) is the way by which the brain represents spatial locations or relations that can be either an object centred (allocentric/intrinsic frame of reference) or body centred (egocentric/relative frame of reference) (Klatzky, 1998). It is important to address problem of how brain (physical entity) represent itself in an objective world in terms of spatial relations (Grush, 2000). Extending to the problem, Grush (2000) classified different spatial representations into the categories of egocentric space(up , here etc.), egocentric space with a non ego object reference point (left , right etc.),object centred reference frame, virtual point of view (neutral perspective) and objective or nemocentric maps. The last two of these five classes referred to allocentric space.

If we include only one kind of spatial relation and expresses locations relative to one point of reference, then it will be defined as elementary spatial representation (Meilinger & Vosgerau, 2010). Elementary spatial representation refers to a person’s default predilection for using either egocentric or allocentric spatial representation when carrying out spatial tasks. In egocentric RF, coordinates of spatial locations are oriented towards navigators and they constantly get updated during movements(i.e. sensorimotor contingencies) while in an allocentric RF, coordinates of spatial locations are independent of the observer's location and are assigned through relations built on the objects and the environmental layout. The dichotomy in spatial reference frame is also supported in the neuroscience research. For example, there exists different neural structures and visual processing pathways for egocentric and allocentric RFs (Galati, Lobel, Vallar, Berthoz, Pizzamiglio, and Le Bihan, 2000 and Holdstock, Mayes, Cezayirli, Isaac, Aggleton, and Roberts, 2000).

Although researches have been more focused on adult population, we chose adolescent for our study. One of the reasons was to explore variation of these representations in the adolescence period which could be benefited from more engagement of participants for the given tasks. However, in children, different developmental trajectories of spatial representation are seen from birth(body centred) to age of 3 to 6 years(object centred) (Nardini, Burgess, Breckenridge, and Atkinson, 2006) which is not affecting factor in our sample . Along with it, teenagers get ability of informal deductions by this age which is one of the required components in a spatial ability. It should be noted that despite the distinction between teenager and children, we used the 'children' interchangeably to refer to the adolescent participants.

Spatial representation is crucial in functioning of everyday life, such as updating orientation or maintaining visuospatial abilities. The role of elementary spatial representation in performing tasks, which require spatial ability, is important. Lot of researchers have quantitatively identified the role of spatial representation in object visualisation (Asakura & Inui, 2011), orientation (Hegarty, & Waller, 2005), wayfinding (Goeke, Kornpetpanee, Koster, Fernandez-Revelles, Gramann, and Konig, 2015), and spatial updating (Burgess, 2006; Tsuchiai, Matsumiya, Kuriki, and Shioiri, 2012; Wang & Spelke, 2002). Very few of them have explored spatial representation in children for various spatial abilities (Bernardino, Mouga, Castelo-Branco, and van Asselen, 2013; Broadbent, Farran, and Tolmie, 2014; Broadbent, Farran, and Tolmie, 2015), but none of them examined teenager. This study assess the role of spatial representation in spatial ability employed in various spatial tasks and wayfinding. In this study, spatial tasks encompass spatial abilities for spatial visualisation, spatial orientation and spatial updating.

Spatial Visualisation is the ability to imagine an object's spatial form and its movement in a desired way. The most commonly used task for measuring this ability is the mental rotation (MR), in which two shapes are compared as similar or different. Several studies of mental rotation have revealed that it requires an object-based spatial transformation irrespective of the egocentric reference frame (Asakura & Inui, 2011; Pani & Dupree, 1994). This reflects that allocentric based transformation is required in mental rotation. We considered object intrinsic reference frame to be equivalent allocentric reference frame following previous works (Campbell, 1995; Levinson, 1996). An assumption that can be formulated based on previous findings is that an individual employing allocentric frame of reference performs better in mental rotation. Another spatial ability, spatial orientation, is defined as the ability to imagine the appearance of objects from different orientations (perspectives) of the observer (McGee, 1979). The test used for this ability is perspective taking test (PT) which is based on egocentric-based spatial transformation (Kozhevnikov & Hegarty, 2001).We assume that an individual who adopt to the egocentric reference frame would perform better in PT.

Spatial updating is a cognitive process that requires the observer to maintain relation between himself/herself and external objects and generate corresponding internal representation in spatial memory. Commonly used task to assess this ability is table top display (TT) task that elicits the representation of spatial relations in memory. These spatial relations can either be egocentric or allocentric. Egocentric relation in spatial memory is influenced by the observer's perspective (Wang & Spelke, 2002) while allocentric relation is influenced by the background objects or the intrinsic orientation of the spatial array (Mou, Fan, McNamara, and Owen, 2008a; Mou, Xiao, and McNamara, 2008b). To summarise, there are two hypotheses for spatial updating, one is egocentric updating hypothesis (Wang & Spelke, 2002) while the other is allocentric updating hypothesis. According to the egocentric updating hypothesis, as we move or when we imagine movement, we update spatial information with respect to the self in the representation of spatial memory (Wang et al., 2006). According to allocentric updating hypothesis, spatial information is updated with respect to objects and environment. To reproduce the information, there is a perpetual debate in literature that if both spatial representations exist together one of them is dominant. Here, in this study, we considered that allocentric reference frame will dominate in TT task, since only table rotation task was performed.

Wayfinding is defined as finding a route from a starting point to a goal. Wayfinding is routine based activity in which efficient route learning is dominated by two strategies, 'landmark-based strategy' and 'directional strategy'. In 'landmark-based strategy', route finding is assisted by easily visible landmarks more synonym with allocentric representation while 'directional strategy' depends on the turns and sensorimotor contingencies, more synonym with egocentric representation. For successful wayfinding in children, landmarks are considered to be a very crucial factor (Kitchin & Blades, 2002; Jansen-Osmann, 2002; Lingwood, Blades, Farran, Courbois, and Matthews, 2015). A recent study demonstrated that route learning based on directions develop after age of 10 and labelled landmarks improved wayfinding in children (Lingwood et al., 2015). This suggests that root cause of these strategies might be use of different spatial representation. For example, a study showed that removal of landmarks pushed typically developing children to adopt sequential egocentric coding for taking directions (Broadbent et al., 2015). Most of the studies focused on importance of landmarks for wayfinding with a single solution(one solution to reach the destination). An important question that needs to be addressed is how landmarks would facilitate wayfinding if there are multiple possible paths i.e. more than one solution to reach the destination. In summary, labelled landmarks would facilitate wayfinding and allocentric RF would dominate in the presence of landmark.

To design the spatial task for spatial orientation (PT), spatial visualisation (MR), spatial updating (TT) and wayfinding(Virtual Maze), there is an intermittent need for precise control of stimuli along with attractive features provided by virtual reality (VR). Virtual reality (VR) provides immersivity which engage participants, especially children, in the task (Parsons & Khosrow-Pour, 2015). Moreover, VR increases the sensory responsiveness of the subject because the subject is not a mere observer but a performer in that task. In addition, it minimizes the omission errors. Therefore, it is a very promising contrivance in assessing spatial tasks more accurately (Freksa, 2013).

Present study

To empirically assess the role of spatial representation in performing a spatial task and wayfinding, we attempt to explore two following objectives, based on the previous studies:

1. If elementary spatial representation does exist then it would remain invariant for short duration spatial tasks which are time bound.

It means that if an individual is classified with respect to his/her default reference frames then he/she would use the same reference frame in all the spatial tasks, even if the task demand would invoke a different strategy. Testing of this hypothesis has been done by examining participants using egocentric and allocentric representations. If the hypothesis is true, participants using allocentric approach would perform better in TT and MR tasks, and participants using egocentric approach would perform better in PT task.

2. If the environment is enriched with landmarks with multiple routes for wayfinding, the participants who are using allocentric reference frame would be more successful in comparison to the participants who would use egocentric reference frame.

Landmarks would facilitate children to complete wayfinding faster in comparison to a virtual maze without landmarks. A landmark enriched environment would facilitate allocentric representation and hence, children using allocentric representation will perform better in a maze with landmarks.

Method

Participants

A total of 65 participants (mean age = 13 years, 30 female and 35 male) were taken volunteered for this study. All of them were right handed, except one male participant. Information consent form was filled by their parents. Consent form was also obtained from the school for conducting the study in their premises. There was no abnormality or learning disorder in the participants and this inference was drawn after interviewing the parents and teachers. Duration for all the experiments put together was one hour. Roughly fifteen minutes were spent in making the children get an idea about the virtual reality technology, the importance of the tasks to be performed, and to habituate them with the computer and mouse.

Apparatus and materials

Animal in a Row Task:

"Animals in a row" task was designed for non-verbal spatial encoding. The main paradigm was adapted from a task developed by Levinson & Schmitt (1993). This task was used to classify participants on the basis of their default reference frame which can be either egocentric or allocentric. Stimuli consisted of three sets of three small toy objects (Animal figures), each of which had a salient front and back. These were placed in a row perpendicular to and in front of the subject, with the “face” of the object toward the subject.

Virtual Environment:

Four different virtual reality tasks were created using Unity 5.1, which included scripting in C\# and java. VE was presented to the participants using a 15.6 inch HD display in a 16:9 widescreen. Distance between the user and the screen was 55 cm. Participants performed the task using a keyboard and mouse.

Table top display task:

Ten objects having no semantic relations were displayed over a table in random order (Fig.1). Participants were instructed for 10 seconds to remember the objects and their spatial layout. After 10 seconds, four objects disappeared from the table for 5 seconds. They subsequently reappeared, but spatial layout was rearranged by rotating them for 180 degrees clockwise. Now the subjects were told to click on the objects which they thought had disappeared. Number of correct selection of objects, commission and omission errors and response time were taken as the factors to be considered for scoring.

Figure 1. Stimuli presentation in table top display task

Mental Rotation:

Subjects were instructed to compare two figures and then respond whether they were similar or dissimilar (Fig.2). The figures were so screened that the difficulty in understanding them was minimal as the subjects were children. Maximum rotation difference was limited to 180 degrees. A total of ten stimuli were provided to the subjects, with a maximum response time of 15 seconds/stimuli, including the participants’ response. Correct response and response time were taken as MR scores.

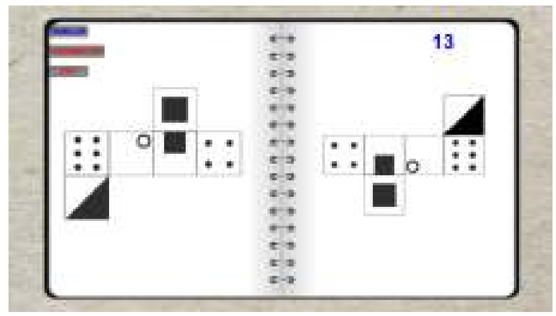

Figure 2. Stimuli presentation in mental rotation task

Perspective Taking Test:

This test was adopted from the perspective taking test of Kozhevnikow and Hegarty (2001). A total of seven objects in a fixed array were shown to the participants. On each item, the participant was asked to imagine being at the position of one object in the display (the station point) facing another object (defining their imagined heading or perspective within the array) and was asked to indicate the direction to a third (target) object (Fig.3). The task was to draw another arrow from the centre of the circle indicating the direction to the target object (e.g. the flower). A total of 12 stimuli were presented to the subject. A total of 30 seconds were given to the participants for making the imagined perspective and then drawing the angle. If the participants responded before 30 seconds, the second stimuli would appear immediately after pressing the next button. Deviations from the correct answer and response accuracy were taken as scores.

Figure 3. Stimuli presentation in perspective taking task (array of object is constant while perspective is changed with each trial)

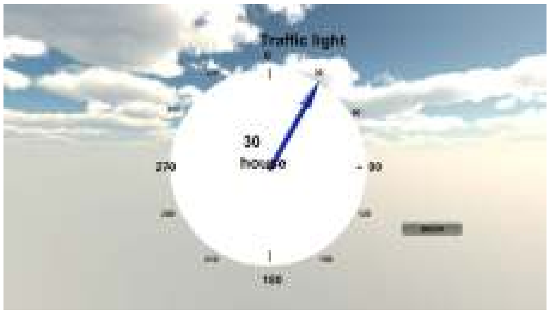

Figure 4. Response format in perspective taking task

Virtual maze:

The demo maze was similar to the test maze to get the children acquainted with the task (Fig.5). It had many landmarks and one solution. The test maze had four varieties. These varieties were designed to identify the efficiency of finding a solution and the role of landmarks in wayfinding. The task was to find a path from home to school. The four varieties included single path (SP), single path with landmark (SPLM), multiple paths (MP) and multiple paths with landmark (MPLM). Single path constituted only one solution available to the participant for wayfinding, whereas multiple paths constituted more than one solution. In this experiment, the participants were instructed to choose the shortest path. Each variety had two types except MP; seven mazes were shown to the participants. In each maze the subjects were instructed to find out the path from home to school. Time taken to plan the route was considered to be the planning time. When the subject had found the path or found the solution then he/she clicked on "play" button and started moving from home to school through keypad arrow key. The time taken to complete the navigation was termed as navigation time. The total time taken on the task was the sum of planning time and navigation time. A maze with landmarks helped them in finding a solution much faster because the following instruction was given to them: “Shortest path includes x, y and z in your way”. Here x, y and z represented different landmarks. In this research study, a total of 8 landmarks were chosen: Bakery shops, mall, grocery store, metro, car parking, cinema hall, stationary shop and a defence organisation. Scores were taken in the form of planning time and total time taken to complete the task. Complexity in wayfinding was balanced in all the mazes

Figure 5. Demo version of the virtual maze

Procedure

The experiment was conducted in an interference-free environment to prevent the participants from getting distracted. Based on the Animal in a row task, the participants were qualitatively classified as adhering to an allocentric or egocentric spatial reference frame. There were three trials in this task. For each trial, two square tables were placed such that a small space was left between them; the subject stood between the two tables and looked toward one of them. The three objects were then placed in a horizontal row on the table in front of the subject, equidistant from each another. The interviewer then pointed to each object in a randomly-selected order, and asked the subject to identify each object placed on the table twice, first by name and then by colour. This was done so that the subject attends to each object in the scene without explicitly invoking spatial language.

The participants had to memorize an array of objects (fish, octopus and scorpion) for some time (15 sec). After some delay, the participants were asked to close their eyes and rotate by an angle of 180 degrees. Then they were shown five objects (an extra shark and a tortoise) and identify three objects from them. This three-of-five procedure was used to increase memory demand and mask the spatial nature of our task.

They were instructed to place the identified objects “in the same way as before” on the table. The participants responded either with absolute placement or relative placement, which then categorised them as allocentric or egocentric respectively. After participant's classification based on their use of default reference frame, next four stimuli were presented in a random order to eliminate any possible sequence effects or any kind of exposure.

The participants handled the mental rotation task, commeasuring to the given instructions. A brief demo was provided to the participants to familiarise them. Similarly, the participants had to undergo the perspective taking test, table-top display test and the virtual maze, in that particular order. Of course, they were aided if they could not grasp the instructions or could not understand the environment. All the trials were presented in a randomised order to counterbalance between participants. For the convenience of the experiment, participants with an allocentric representation were referred to as the group 'A' and participants with an egocentric representation were referred to as the group 'E'.

Results

The "Animal in a Row" task classified 65 students into the group A (25 students) and group E(40 students) with respect to object placement on a table. According to the classification, scores were distributed among groups and further evaluated using statistics in R 3.0. Descriptive statistics of scores are displayed in Table-1(MR, PT, and TT) and Table-2 (VM). To avoid any gender biases in our results, we did Pearson Chi Square statistics to identify effect of gender on variables of the spatial tasks. There was no effect of gender on the PTA, $\chi^2(2, n=64)=0.1773, p>0.05$, MR, $\chi^2(3, n=59)=1.55, p>0.05$, and TT, $\chi^2(3, n=64)=0.44, p>0.05$. Group E had more correct responses, $t(58)=0.68, p>0.05$, and less response time, $t(58)=1.32, p>0.05$ in MR task, while, Group A had a greater response accuracy(correct answers/number of stimuli attempted), $t(63)=0.49, p>0.05$, along with more deviation, t(63)=0.35, p>0.05 in PTA task. In TT task, group E had more number of correct responses, t(63)=0.36, p>0.05,with more errors, t(63)=0.76, p>0.05, and less response time, t(63)=0.34, p>0.05. We calculated percentage accuracy (maximum correct response covered by group/ total number of correct response *100) assess performance in group. Percentage accuracy for correct response in each task, Mental rotation (group A=49.56\% , group E=52.97\%), Perspective taking test (group A=55.13\%, group E=41.56\%) , and table top display (group A=47.82\%, group E=50\%), was in concurrency of above stated findings.

One-way ANOVA was applied on the obtained variables of virtual maze. Group A showed lesser planning time for the maze having landmarks, F(1,59)=4.37, P>0.05, while, Group E showed lesser total time for single path, F(1,59)=5.26, P>0.05,and multiple path, F(1,59)=8.19, P>0.05. Both groups had lesser total time for maze enriched in landmarks. Group A took less time in reaching destination for multiple path with landmarks, F(1,59)=6.18, P<0.05, shown in table 3.

Table 1. Descriptive statistics in group A (Allocentric reference frame) and group E (Egocentric reference frame).

Task	*Scoring variable*	*Group E*		*Group A*	
		Mean	*SD*	*Mean*	*SD*
Mental Rotation	Correct Response	5.29	1.41	4.95	1.46
	Response time (in second)	7.66	2.05	7.27	1.52
Perspective Taking Test	Deviation from correct response	26.77	82.91	34.64	71.44
	Response accuracy	29.93	17.22	31.97	17.22
Table Top Display	Correct Response	3.69	1.37	3.54	1.71
	Response Time	35.05	14.91	38.76	34.22
	Commission Error	1.7	0.91	1.64	1.18
	Omission Error	2.00	0.96	1.92	0.86

Table 2. Performance of groups in different types of virtual maze

Groups	*Varieties in maze*	*Planning*		*Total time taken*	
		Mean	*SD*	*Mean*	*SD*
Allocentric	SP1	34.86	35.78	79.50	49.31
	SP2	50.91	40.28	114.16	62.12
	SPLM1	19.13	14.45	50.64	18.13
	SPLM2	29.71	21.23	77.18	32.30
	MP	28.00	21.29	61.81	30.53
	MPLM1	26.26	13.78	60.54	23.43
	MPLM2	26.00	16.76	53.08	18.41
Egocentric	SP1	30.21	17.57	58.97	20.87
	SP2	52.28	51.90	110.00	60.23
	SPLM1	23.29	19.57	57.45	38.45
	SPLM2	31.72	28.98	78.23	39.69
	MP	27.36	17.58	43.18	19.53
	MPLM1	39.46	26.91	59.85	39.96
	MPLM2	32.05	21.11	70.00	28.65

Table 3. Independent sample t-test differences between the two groups

Type of Virtual Maze	*T test value for total time taken*
SP1	5.26*
SP2	0.55
SPLM1	0.90
SPLM2	0.01
MP	8.19**
MPLM1	0.02
MPLM2	6.18*

Notes: * $p < .05$, ** $p < .01$.

Discussion

The present study explored the role of allocentric vs. egocentric spatial representation in various spatial task and wayfinding. It also addressed the influence of spatial representations during performance when labelled landmark was presented in virtual maze. The question addressed in the study was: In case of a time bound task, would a subject use the default reference frame or not? In this paper, the hypothesis 1 states if it is classified that a participant uses a particular spatial representation for performing a spatial task(which is termed as default in this paper) , then would he/she use the same representation in all the spatial tasks, irrespective of their individual and task demands. For MR and PT tasks, we inferred from previous researches that the participant using an allocentric representation would perform better in the former task and the participant using an egocentric representation would perform better in the latter task (Hegarty & Waller, 2004; Menchaca-Brandan, Liu, Oman, and Natapo, 2007). Our result showed that participants who were classified in group A had more response accuracy in Perspective taking test, while participants who were classified in group E had more correct response in mental rotation task. This result contradicted the assumption; therefore, the hypothesis was rejected. Inference could be drawn that if a person has been classified to be using a certain spatial reference frame, he/she can switch over to the other reference frame, based on the demands of the task. Consistent with the earlier research, the results indicated that both the abilities (spatial visualisation and spatial orientation) were dissociated on the basis of applied spatial transformation strategies ((Hegarty & Waller, 2004; Menchaca-Brandan et al., 2007) These strategies are determined on the basis of spatial representation for a particular task. If participants are classified on the basis of their default spatial representation for small scale scene, then probability of choosing that representation in another spatial task increases. When properties of the task demand for the strategy (or working out with different spatial relation/representation) different from the default one, the participant's load increase, and he can either switch to other strategy or use default one. Time consumption increases while utilising default spatial representation for opposing demands as evident from deviated outcome of expectation for MR and PT tasks in group A and group E respectively.

In case of the TT, participants using an allocentric representation would perform better because the observer's locomotion was static. Results showed that Group E had a higher score and shorter response time which disagreed with our assumptions. Participants having egocentric representation performed better because there was no need for them to switch over from a transient to an enduring representation owing to its pronounced effect on disorientation (Waller & Hodgson, 2006). Since the task was displayed in VR without adding any environmental boundaries, the ego group had a greater score (Burgess, Spiers, and Paleologou, 2004). However, rise in errors indicated participants of group E had lack of alignment of the intrinsic axis over the imagined viewpoints. In addition, the locations of the objects were also stored along with the intrinsic axis, which reduced the errors in the allocentric representation (Burgess, 2006). Therefore, we concluded that first hypothesis could not be accepted for spatial updating task, according to which, if one uses default reference frame, it might not be necessary that the spatial updating would also be in the same reference frame.

For spatial tasks like mental rotation, perspective and table-top display task, first hypothesis was rejected. The major reason for the rejection of hypothesis could be that the priority of selection would be higher for default/habitual spatial representation, but the probability of switching between the representations becomes predominant when task demands different strategy. The proportion and amount of change in the representation is in itself flummoxing, which can become part of future research.

In wayfinding task, our assumptions were that egocentric approach would be better in case of no landmarks and allocentric approach would otherwise be better. The virtual maze enriched in landmarks had facilitated wayfinding, putting emphasis on importance of landmarks for the participants. These findings matched with the previous results (Lingwood et al., 2015), though they pertain to only single-path solutions. There is only one way to reach one's home from the target location. According to our knowledge, no one has specifically worked on multiple-path solutions for children in which there are multiple paths to reach one's home from the target location. Our results demonstrated that in multiple-path solution, both the groups took less time when compared to single-path solution. It means that when people were given choices, the teenager's way finding ability increased, because multiple solutions increase the likelihood of way finding by decreasing the problem space.

As expected, Group A performed better than Group E in wayfinding provided there were landmarks. On the account of the gathered results, it was speculated that the probability of choosing the default reference frame increases in certain given conditions for wayfinding. The given conditions in our experiment were: a) no time limitation, b) retracing the path to the destination from origin was not allowed and c) the view of the participant should not change (i.e. the home and the target should be displayed on a single screen). Thus, summarising the wayfinding task provided the certain conditions mentioned above, both the hypotheses were accepted.

Conclusion

To sum up, the objective of this study has been to find out whether default spatial representation differs or remains the same in different spatial tasks utilizing different spatial ability. In addition, this study intended to test how these spatial representations help an individual when he/she is facing a problem with multiple possible paths in the presence of landmarks and without landmarks. Result suggests that if an individual is using a particular type of representation for a particular task, it is possible for him/her to effectively switch over from one representation to another for a different task. We bring it to the knowledge of the readers that the spatial representation is elementary in nature as some groups acknowledged that it could be sequential or parallel as well. The findings suggest that children could switch over from one spatial representation to another or could stick to their spatial representation. It was also shown that the landmarks, which facilitated wayfinding with multiple-paths and also that children using an allocentric representation performed better. What makes this study stand out is that it attempts at gauging the overall spatial ability in children through wayfinding, something that has not been explored so far. Also, it contributes in ameliorating the draught of work pertaining to classifying reference frames in the field of spatial cognition. Yet another factor that renders this study unique lies in the fact that although research so far has been done with children subjected to a maze, no work had been thoroughly dedicated to check the efficacy of the landmark approach in the case of multiple possible solutions to reach a goal.

Acknowledgement

The authors would like to thank to the Director of INMAS and Hyundan Model School. This research was funded by INMAS, DRDO-Delhi. We would also like to thank Mary Hegarty and Kim Kastens for helping in scoring in Perspective taking test.

References

Asakura, N. and Inui, T. (2011). Disambiguation of mental rotation by spatial frames of reference. *i-Perception*, *2*(5):477.

Bernardino, I., Mouga, S., Castelo-Branco, M., and van Asselen, M. (2013). Egocentric and allocentric spatial representations in williams syndrome. *Journal of the International Neuropsychological Society, 19*(01):54-62.

Broadbent, H. J., Farran, E. K., and Tolmie, A. (2014). Egocentric and allocentric navigation strategies in williams syndrome and typical development. *Developmental science*, *17*(6):920-934.

Broadbent, H. J., Farran, E. K., and Tolmie, A. (2015). Sequential egocentric navigation and reliance on landmarks in williams syndrome and typical development. *Frontiers in psychology*, 6, 216-223.

Burgess, N. (2006). Spatial memory: how egocentric and allocentric combine. *Trends in cognitive sciences*, *10*(12), 551-557.

Burgess, N., Spiers, H. J., and Paleologou, E. (2004). Orientational manoeuvres in the dark: dissociating allocentric and egocentric influences on spatial memory. *Cognition*, *94*(2), 149-166.

Campbell, J. (1995). *Past, space, and self*. MIT Press.

Freksa, C., Brauer, W., Habel, C., & Wender, K. F. (Eds.). (2003). *Spatial cognition III: Routes and navigation, human memory and learning, spatial representation and spatial learning* (Vol. 2685). Springer.

Galati, G., Lobel, E., Vallar, G., Berthoz, A., Pizzamiglio, L., and Le Bihan, D. (2000). The neural basis of egocentric and allocentric coding of space in humans: a functional magnetic resonance study. *Experimental Brain Research*, *133*(2), 156-164.

Goeke, C., Kornpetpanee, S., Koster, M., Fernandez-Revelles, A. B., Gramann, K., and Konig, P. (2015). Cultural background shapes spatial reference frame proclivity. *Scientific reports*, 5.

Grush, R. (2000). Self, world and space: The meaning and mechanisms of ego and allocentric spatial representation. *Brain and Mind*, *1*(1), 59-92.

Hegarty, M. and Waller, D. (2004). A dissociation between mental rotation and perspective-taking spatial abilities. *Intelligence*, *32*(2), 175-191.

Hegarty, M., & Waller, D. (2005). Individual differences in spatial abilities. *The Cambridge handbook of visuospatial thinking*, 121-169.

Holdstock, J., Mayes, A., Cezayirli, E., Isaac, C., Aggleton, J., and Roberts, N. (2000). A comparison of egocentric and allocentric spatial memory in a patient with selective hippocampal damage. *Neuropsychologia*, *38*(4), 410-425.

Jansen-Osmann, P. (2002). Using desktop virtual environments to investigate the role of landmarks. *Computers in Human behavior*, *18*(4), 427-436.

Kitchin, R., & Blades, M. (2002). *The cognition of geographic space* (Vol. 4). Ib Tauris.

Klatzky, R. L. (1998). Allocentric and egocentric spatial representations: Definitions, distinctions, and interconnections. In *Spatial cognition* (pp. 1-17). Springer Berlin Heidelberg.

Kozhevnikov, M. and Hegarty, M. (2001). A dissociation between object manipulation spatial ability and spatial orientation ability. *Memory & Cognition*, *29*(5), 745-756.

Levinson, S. C. (1996). Frames of reference and Molyneux's question: Crosslinguistic evidence. *Language and space*, 109-169.

Levinson, S. C., & Schmitt, B. (1993). Animals in a row. *Cognition and Space Kit Version*, *1*, 65-69.

Lingwood, J., Blades, M., Farran, E. K., Courbois, Y., and Matthews, D. (2015). The development of wayfinding abilities in children: learning routes with and without landmarks. *Journal of environmental psychology*, *41*, 74-80.

McGee, M. G. (1979). Human spatial abilities: psychometric studies and environmental, genetic, hormonal, and neurological influences. *Psychological bulletin*, *86*(5), 889.

Meilinger, T., & Vosgerau, G. (2010, August). Putting egocentric and allocentric into perspective. In *International Conference on Spatial Cognition* (pp. 207-221). Springer Berlin Heidelberg.

Menchaca-Brandan, M. A., Liu, A. M., Oman, C. M., & Natapoff, A. (2007, March). Influence of perspective-taking and mental rotation abilities in space teleoperation. In *Proceedings of the ACM/IEEE International Conference on Human-robot interaction* (pp. 271-278). ACM.

Mou, W., Fan, Y., McNamara, T. P., and Owen, C. B. (2008a). Intrinsic frames of reference and egocentric viewpoints in scene recognition. *Cognition*, *106*(2), 750-769.

Mou, W., Xiao, C., and McNamara, T. P. (2008b). Reference directions and reference objects in spatial memory of a briefly viewed layout. *Cognition*, *108*(1), 136-154.

Nardini, M., Burgess, N., Breckenridge, K., and Atkinson, J. (2006). Differential developmental trajectories for egocentric, environmental and intrinsic frames of reference in spatial memory. *Cognition, 101*(1), 153-172.

Pani, J. R., & Dupree, D. (1994). Spatial reference systems in the comprehension of rotational motion. *Perception*, *23*(8), 929-946.

Parsons, T. D. (2015). Ecological validity in virtual reality-based neuropsychological assessment. *Information Science and Technology,* 214-223.

Shioiri, S. (2012). Implicit learning of viewpoint-independent spatial layouts. *Frontiers in psychology*, *3*, 207-214.

Waller, D., & Hodgson, E. (2006). Transient and enduring spatial representations under disorientation and self-rotation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *32*(4), 867.

Wang, R. F., Crowell, J. A., Simons, D. J., Irwin, D. E., Kramer, A. F., Ambinder, M. S., Thomas, L. E., Gosney, J. L., Levinthal, B. R., and Hsieh, B. B. (2006). Spatial updating relies on an egocentric representation of space: Effects of the number of objects. *Psychonomic bulletin & review*, *13*(2), 281-286.

Wang, R. F. & Spelke, E. S. (2002). Human spatial representation: Insights from animals. *Trends in cognitive sciences, 6*(9), 376-382.