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Impact of the spatial structuring of virtual towns on the navigation strategies of children aged 6 to 15 years old

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ABSTRACT

Individuals navigating a space use two strategies: adults mainly use a 'counting' strategy (i.e. numbering or counting the intersection in the town; memorising a series of left and right turns from a given starting position), children rely more on a 'response' strategy (i.e. using reference points or landmarks; turn after the blue building). A lot of research into spatial cognition requires the use of virtual environments and uses regular environments ('Cartesian grids, Squareland or city-block raster' (Hamburger and Knauff, 2011), 'radial maze' type (Astur, Tropp, Sava, Constable and Markus, 2004), etc.) but few studies have focused on how children and adolescents learn to memorise an itinerary in a less regular environment (Nys, Gyselinck, Orriols and Hickmann, 2015). The originality of this work is to understand how children and adolescents learn to memorise an itinerary in a developmental perspective (participants aged 6 to 15 years old). The intention is also to identify any development in the strategies when the children and adolescents reproduce a route in two differently structured environments (cities with a regular or irregular plan). The results of the first experiment, conducted with V-Squarecity (a regular environment), show that the environment does not require the employment of response strategies, but may give rise to strategies for organising/storing spatial information (counting strategies). It will also be shown that younger children use response strategies and that older children develop counting strategies. The result of the second experiment, conducted with V-Sinuouscity (an irregular environment), reveal the reduced use of counting strategies. This work emphasises the need to take account of the nature of simulated spaces during studies on spatial strategies.

Keywords: *Spatial cognition, Virtual reality, Navigation strategies, Structure of the environment, Child development, Adolescent development.*

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1. Introduction: Studies into the Impact of Environment Structure on Spatial Performance

In many areas, including, of course, spatial cognition, the use of virtual environments has shown its effectiveness and potential for learning various skills and for the analysis of an individual's cognitive and behavioural functioning (Klinger, Marie and Fuchs, 2006). Virtual reality can be defined, more technically, as 'a scientific and technical field which uses computing and behavioural interfaces to simulate, within a virtual world, the behaviour of 3D entities which interact in real time with each other and with one or more users in pseudo-natural immersion through sensorimotor channels' (Arnaldi, Fuchs and Guitton, 2006; Fuchs, Arnaldi and Tisseau 2003). The fact that virtual environments are created to enable specific actions to be performed must be added to this definition.

Virtual reality applications, which enable the simulation of locomotive activities (go forward, turn right, turn around, go left, etc.) in configured environments, are increasingly used in spatial cognition. In order to work out where they are, orient themselves (Pierre and Soppelsa, 1998) and be able to decentre (Beaudichon and Bideaud, 1979; Borjon Sultan, 2010; Piaget and Inhelder, 1975;), individuals must acquire, develop and exercise spatial knowledge and abilities. Questions relating to spatial learning, the development of the spatial sense, orientation and so on are not new (Piaget and Inhelder, 1975), however, since the advent of new technologies, such as virtual reality, research into spatial cognition has increased (e.g. Farran, Courbois, Van Herwegen, Cruickshank and Blades, 2012; Jansen-Osmann and Berendt, 2002; Wallet, Sauzéon, Larrue and N'Kaoua, 2013; Wallet, Sauzéon, Rodrigues and N'Kaoua, 2009). While it is not possible to exercise precise control over all the variables in a real environment, or even to carry out all the operations within it that would be required in order to answer questions about a particular spatial skill, this has become achievable through the use of virtual reality (Kelly and Gibson, 2007). The use of virtual reality also allows activities to be carried out under safe conditions. Thus, in the case of the experiments conducted here, the participants were able to move around in risk-free urban environments where the experimental conditions were strictly identical and did not vary as a result of the experimenter or various unpredictable factors. The use of virtual reality thus makes it possible to replicate a study on a large number of subjects without introducing any bias into the results (Peters, Wu and Winter, 2010). In addition, virtual reality makes it possible to record, in real time, an individual's activity and performance in terms of behavioural, cognitive, motor and/or physiological components (Klinger, 2008). As such, most of the actions performed by the subject can be quantified in a simultaneous, precise and natural manner, without the subject being aware of it. Virtual environments, therefore, are useful assessment tools for studying behaviour and cognition in the field of spatial learning (Fuchs and Moreau, 2003; Grumbach and Klinger, 2007; Kelly and Gibson, 2007; Stankiewicz, Legge, Mansfield and Schlicht, 2006). What's more, due to its modular nature, virtual reality allows us to build different environments. In this paper, the environments created are cities defined by a regular or irregular plan.

To our knowledge, not many studies have looked at the influence of the structure of an environment on how individuals perform in spatial exercises (Herman, Blomquist and Klein, 1987; Jansen-Osmann and Heil, 2007; Jansen-Osmann, Schmid and Heil, 2007a). Likewise, only a few of these studies have looked at the reproduction of routes. This study particularly focuses on the knowledge of routes (by the reproduction of routes) in differently structured environments. With reference to the taxonomy of Siegel and White (1975), this type of knowledge involves learning sequences of landmarks, segments of angles and actions performed while navigating through an environment (Golledge, 1999; Thompson, Fleming, Creem-Regehr and Stefanucci, 2011;). Knowledge of the route can be defined as a form of procedural knowledge including several sequences, for example, the start point, end point and intermediate stopping points (Allen, 1999). This type of knowledge is acquired through personal experience in a given environment, with reference to an egocentric framework, and depends on visual memorisation (Bullens, Igloi, Berthoz, Postma and Rondi-Reig, 2010; Darken and Goerger, 2000). It is by navigating the environment that individuals perceive and record the stimuli encountered, such as landmarks, location of landmarks, relationship between landmarks, etc.

Most experiments to date assess either the ability to estimate the distances and directions travelled, for example, by pointing out landmarks or the starting point, or they assess the ability to find shortcuts. An experiment conducted by Herman et al. (1987) showed that the structure of the real environment does not affect spatial knowledge. These researchers showed that the performance of children and adults, measured in terms of estimates of distance and 'bearing distance estimate', is the same in real environments of the 'Cartesian grids' type or with curved segments. Other experiments in virtual environments have sometimes confirmed, and sometimes contradicted, these results. While Jansen-Osmann, Schmid and Heil (2007a) point to the fact that the regularity or irregularity of the environment has no effect on the spatial knowledge of children and adults, measured in terms of estimates of direction and distance travelled in route knowledge and detour tasks, Jansen-Osmann and Heil (2007) indicate that learning a route in a circular environment is more effective than learning it in a square environment, and that the structure of the environment influences the different stages in the acquisition of spatial knowledge for both children and adults. Another study by Jansen-Osmann, Schmid and Heil (2007b) concluded that the regularity and symmetry of the environment's structure have a partial influence on spatial cognition by improving wayfinding, but without any impact on spatial knowledge, and exclusively in young children. Based on the work of other authors working with adult subjects (Tversky, 2000), a dual explanatory hypothesis has been proposed: as children grow up, they become able to smooth out the irregular features and spatial knowledge becomes more and more independent of the structure over time. However, although the overall structure of the environments used by Jansen-Osmann and Heil (2007) was different, it was still fairly regular (Figure 1).

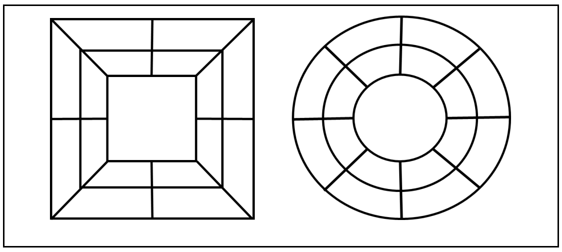

Figure 1. Diagram of the environments used in research by Jansen-Osmann and Heil (illustrations adapted from Jansen-Osmann and Heil, 2007)

Most studies in spatial cognition use regular environments, and some authors invite the scientific community to adopt such environments. For example, Hamburger and Knauff (2011) have developed a regular environment called ‘squareland’, which allows ‘researchers to quickly implement experiments on indoor- and outdoor wayfinding, including variations of route length, route complexity, availability of landmarks, etc’. Recent work initiated by Bohbot et al. (2012) has shown that in a regular environment, children mainly use a strategy based on using landmarks, and the relationship between landmarks, which depends on the hippocampus. Young adults and older adults, on the other hand, use a strategy based on memorising a series of left and right turns from a given starting position, which depends on the caudate nucleus. These sometimes contradictory results, and consideration of the physiology of the processes used, raise questions about the processes that are really activated by users during spatial tasks carried out in a virtual environment, and the impact of the nature of this environment.

Few studies have focused on how children and adolescents learn to memorise an itinerary in a less regular environment and no research has been conducted about it in a developmental perspective. The originality of this work is to understand how children and adolescents learn to memorise an itinerary. The second originality is to identify any development in the strategies when the children and adolescents reproduced a route in structured environments differently, either in cities with a regular or irregular plan. In this paper, some results will be presented in a developmental perspective. The participants' ages ranged from 6 to 15 years old. First the research hypotheses will be introduced and the material and methods to carry out the two experiments with different environments will be presented. V-Squarecity, a city defined by regular plan, and V-Sinuouscity, a city defined by an irregular plan, will then be then presented. After that, the results of two experiments carried out will be detailed and the paper will be concluded and indications for future works provided.

2. Research Hypotheses

In view of the few studies investigating the structure of the environment, the authors formed the hypothesis that the use of regular environments, such as that proposed by Hamburger and Knauf (2011), favours counting strategies over response strategies requiring spatial skills. In order to test this hypothesis, the experiment presented here investigates the cognitive strategies used by subjects when they have to reproduce a path in two kinds of unfamiliar virtual environment (for more information about the strategies, see, among others, Vidal, 2002).

Behind the general hypothesis that the strategies implemented by individuals depend on the complexity and regularity of the situations encountered, several underlying hypotheses take shape. The first of these hypotheses, relating to the effect of complexity on subjects' performance, concerns the length of the route. In the environment, each crossroad is a decision point (nDP = number of decision points), irrespective of direction change or not (turn or go straight ahead). In other terms, nDP is the number of crossroads where the subject is required to make a choice about which direction he or she wishes to take. Then, the length of the route depends on the number of decision points and can be studied when the number of direction changes (nIP = number of inflection points) remains constant. A nIP is a crossroad where the subject must change direction. According to this first hypothesis, a route with fewer decision points will be followed more successfully than one with a higher number of decision points (Hypothesis 1).

The number of inflection points (nIP) can also be varied while keeping the number of decision points constant. The second hypothesis is formulated as follows: increasing the number of changes of direction will affect the performance of subjects. According to this reasoning, a route with fewer inflection points will be followed more successfully than one with a higher number of inflection points (Hypothesis 2).

With regard to strategies, Bohbot et al. (2012) found in their study that in a regular environment, in this case, a radial maze, children prefer to use a response strategy by using landmarks, whereas young adults and older adults make more use of a counting strategy (numbering or counting the ‘branches’ of the maze). Since it appears that a change in strategy occurs before adulthood, the experiment presented here was carried out with children and adolescents aged from 6 to 15 years old, postulating that during childhood a change of strategy takes place (Hypothesis 3). To the two strategies clearly identified by Bohbot et al. (ibid.), a third is added here as a hypothesis. This is a mixed strategy combining use of landmarks (response strategy) and counting, the appearance of which may depend on the complexity of the environment and the level of development of the subjects (Hypothesis 4). Thus, referring to the concept of ‘cognitive equilibration’ (Piaget, 1975), it may be imagined that a child in difficulty tries to adapt to the environment in which they are moving by a process of assimilation/accommodation.

A final hypothesis (Hypothesis 5), formulated by the authors during the experiment, relates to the influence of the environment's irregularity, and hence the predictability, on the use of one strategy in preference to another. In a regular environment (V-Squarecity), the preferred strategy, at a given age, consists of synthesising the information and storing it in the form of chunks. In an irregular environment, this choice of strategy proves less effective and leads to preference being given to response strategies, which involve memorisation of the visual cues present and their organisation.

3. Material and Methods

The experiment to which this article relates was conducted in two stages, requiring the implementation of two virtual environments with different properties. For each virtual environment, described below, a specific protocol was developed. This is presented in points 3.1. 'First experimental phase: use of V-Squarecity' and 3.2. 'Second experimental phase: combined use of V-Squarecity and V-Sinuouscity'.

To carry out the experiments, two virtual cities were generated. The first virtual environment, called V-Squarecity (virtual Squarecity), recreates a large city organised according to a Hippodamian plan (see Figure 2). This regular plan is characterised by roads that intersect at right angles, thus creating square or rectangular blocks (Louail, 2010). The second environment, called V-Sinuouscity, simulates a virtual city of the same size, but organised according to an irregular plan (Figure 3).

The differences here are that on the regular plan road sections are of the same length, and on the irregular plan roads depart from a central point and are connected together by roads of varying lengths. Thus, on the irregular plan, the roads are not perpendicular to one another, and may have several branches to the right and/or left, which is impossible in the regular plan, and which complicates the synthesis of spatial information systematically. No clues such as street names are given in either of the virtual environments. The speed of movement within the environment is constant, which gives the subject information about the length of routes. Thus, in the regular city, it is possible for the child to notice the differences in the length of streets.

Although it is now possible to design very realistic environments (Larrue, 2011), the objective of the study was to develop and test a simple environment in which the different characteristics of the structure can be modified. In the basic version of the two environments, the simulated city consists of grey buildings with light grey windows. Using both qualitative and quantitative settings, the two virtual environments were designed with Esri City Engine® into which the game engine Unity® was integrated. Qualitative settings include the nature of landmarks, the variation of the colour of the façades and the height of the buildings, etc., whereas examples of quantitative settings are the percentage of landmarks and the percentage of coloured façades, etc.. The boundaries of both cities (Lynch, 1960) were represented by empty space. Like the other parameters, the subject's viewpoint could be changed. For the purposes of this experiment, the viewpoint adopted was exclusively egocentric: the camera was placed at eye level, to give a first-person or ground-level perspective, and not in flying mode, which gives an aerial perspective (Lin et al., 2012; Wallet et al., 2013).

In this, environment three common activities relating to spatial orientation can be carried out. One of these involves exactly reproducing a route that has already been travelled following blue markers (reproduction route). The other two activities, which are not covered in this article, consist of (1) following a marked route and then travelling the same route in reverse, but without the blue markers (decentration route) (Beaudichon and Bideaud, 1979; Borjon Sultan, 2010) and (2) finding shortcuts for a route which has been taken following the blue markers (integration path).

The individual's activity is an important aspect; individuals can navigate at their own pace and thus store the information they deem necessary according to their movements.

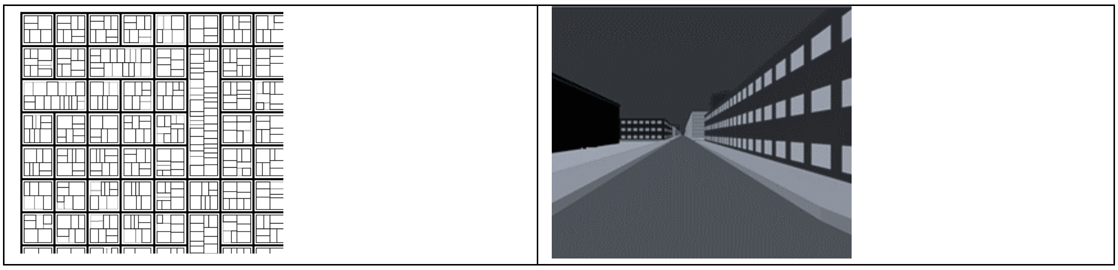

Figure 2. Illustrations showing the virtual environment of V-Squarecity, regular type (map on the left and egocentric view on the right)

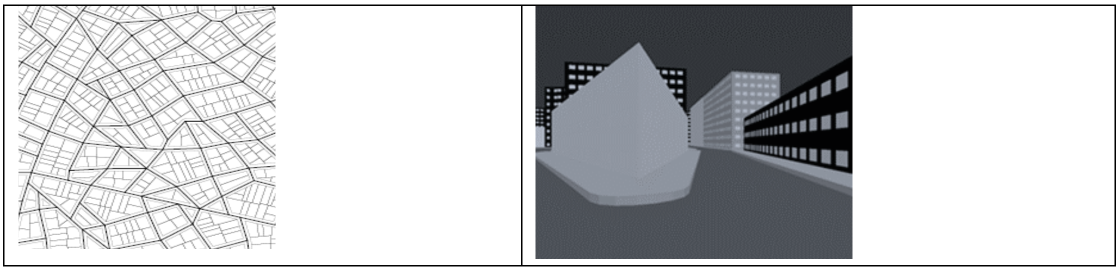

Figure 3. Illustrations showing the virtual environment of V-Sinuouscity, irregular type (map on the left and egocentric view on the right)

3.1. First Experimental Phase: Use of V-Squarecity

In the V-Squarecity environment, thirteen reproduction routes were defined (Table 1). These were characterised by a number of decision points (nDP) and a number of inflection points (nIP). In this way, routes of varying lengths (with between 5 and 13 decision points) with more or fewer changes of direction (between 1 and 5 inflection points) were set for the participants. A decision was taken not to set routes with three inflection points, in order to limit the duration of the experiment. The order in which the routes were presented was determined randomly and all pupils covered the thirteen routes in the same order (1 to 13).

Table 1. Reproduction routes taken in V-Squarecity during the first experimental phase

Reproduction route (in order of presentation)	nDP	nIP
Route 1	7	1
Route 2	5	2
Route 3	9	2
Route 4	9	5
Route 5	5	1
Route 6	13	5
Route 7	9	1
Route 8	13	2
Route 9	7	4
Route 10	13	1
Route 11	9	4
Route 12	13	4
Route 13	7	2

Participants

This experiment was conducted with 113 children aged 6 to 15. Groups of 23 children were formed based on age categories (6-7 years old, 8-9 years old, 10-11 years old, 12-13 years old, and 14-15 years old). Children with learning disorders (Attention deficit hyperactivity disorder, ADHD) or significant deficits (missing skills in basic functions) were not included in the experiment; some groups therefore only consisted of 22 children or adolescents. The subjects were recruited from primary and secondary schools in the city of Mons in Belgium. The socio-economic characteristics of these schools were average. From a group of 20 classes, each of which represented 5% of the total number of participants, classes 8 to 11 were chosen as the sample to be selected. Children were recruited through advertisements at schools. School teachers gave consent, and both school directors and parents signed a consent form. Participants remained anonymous throughout the data collection. Confidentiality of all data was preserved in accordance with applicable state and federal laws. Pupils were informed they could stop when they wanted to.

Design

In the experiment, subjects were asked to reproduce several routes in succession in a virtual environment, using a joystick. The instructions given before starting the activity were as follows: 'You find yourself in a city that you don't know, and you must follow the path indicated by the blue markers. At the end of the course, there will be a pause. You will then be taken back to your starting point and you will be asked to take exactly the same route again, but without the blue markers.' Initially, the child, who was seated in front of a 25 inch screen, travelled a route in the virtual environment by following the markers (blue dots which indicated the path to follow) using a joystick (behavioural interface), without being able to choose to take a route other than the one marked. Once the child had reached the end of the route, they returned to the starting point and had to reproduce the same route without the markers. Each child had to carry out the same exercise for the thirteen different routes.

After completion of the computer-based exercises, a retrospective verbal report consisting of open or semi-open questions was conducted with each subject separately (Ericsson and Simon, 1980; Tenbrinck, 2008; Tenbrinck, D'Odorico, Hertzberg, Mazman, Meneghetti, Reshoft and Yang, 2012). The purpose of this retrospective verbal report was to ask the child about the strategy or strategies used during the completion of the task and thus to distinguish which strategy or strategies were preferred. The verbal report also helped to identify any changes of strategy made during the activity. In other words, the interview gave a more precise view of the problem-solving strategy or strategies the subject claimed to have used in order to complete the exercises. The questions asked during the interviews were as follows 'At what point were you sure that you had correctly completed the route you had previously followed?' (on a 5-point Likert-type scale); 'What did you do in order to reproduce the route through the city without the blue markers?'; 'What helped you to reproduce the route?'; 'Did you notice anything in particular?'.

At the end of the thirteen routes, the verbal and spatial spans (Corsi blocks) of each child (Auclair and Sieroff, 2002) and their knowledge of laterality and directions (Piaget-Head tests, calibrated by Galifret-Granjon) (Zazzo, 1958) were evaluated to complete the task.

Data Collection

In addition to the reported data collected through the interviews, it was important to record the activity and performance of the individual subjects as they navigated through the virtual environment. The use of computer tools enabled such data to be collected in real time (Klinger, 2008). The data collected were grouped into two categories. The first category concerned data relating to the execution of the task (the time taken by the child when following the marked route; the time taken by the child when reproducing the unmarked route). The second category of data consisted of all coordinates of positions occupied and the time that elapsed when a given position was occupied (X; Y; time). The speed of movement between two points is proportional to the distance travelled. These coordinates enabled the subject's position in the city to be precisely located at any specific time. Using the coordinates, a set of indicators was calculated that enabled the subject's performance to be evaluated (exercise finished with complete success, number of correct decision points before failure, etc.). In this way, it was possible to see the route taken, and study parameters such as distance, travel time or even stops made by the subject at crossroads.

The data collected during the cognitive interviews were coded using spreadsheet software.

3.2. Second experimental phase: combined use of V-Squarecity and V-Sinuouscity

The internal organisation of space and geometry of regular and irregular plans of cities differ (Louail, 2010). The results of the experiment conducted in a regular environment (V-Squarecity) led the authors to develop a second, more irregular, environment (V-Sinuouscity), in order to exercise and encourage individuals' ability to find their way in a given environment.

Table 2. Reproduction routes taken in V-Squarecity or V-Sinuouscity during the second experimental phase

Reproduction route (in order of presentation)	Ndp	nIP	City (V-Squarecity/V-Sinuouscity)
Route 1	5	2	V-Squarecity
Route 2	13	2	V-Squarecity
Route 3	7	4	V-Squarecity
Route 4	13	4	V-Squarecity
Route 5	7	2	V-Squarecity
Route 6	13	2	V-Squarecity
Route 7	***9***	***4***	***V-Squarecity***
Route 8	***5***	***2***	***V-Sinuouscity***
Route 9	13	4	V-Squarecity
Route 10	7	4	V-Squarecity
Route 11	***9***	***4***	***V-Sinuouscity***
Route 12	13	4	V-Squarecity
Route 13	7	2	V-Squarecity
Route 14	***5***	***2***	***V-Squarecity***

Design

As in the previous experiment, participants were asked to reproduce routes already taken, this time in both virtual cities. Two of these routes were in the V-Sinuouscity (see Table 2). There was a route with five decision points and two inflection points (Route 8), and one with 9 decision points and 4 inflection points (Route 11). Routes with the same characteristics were also travelled in the V-Squarecity in order to compare the results. Following each completed route, a cognitive interview identical to that which took place during the first experimental phase of testing was conducted.

Participants, Design and Data Collection

The experiment was conducted with 30 children between 10 and 12 years of age, an age group in which no clearly established preference for strategies can, as yet, be observed (see Results, Figure 7). As in the previous experiment, the subjects were asked to reproduce routes through the city. The same exclusion criteria as in the first phase were applied.

The same design as described for the first phase was used. The same data collection protocol was used with the recording of data from the virtual environment and cognitive interviews.

4. Results of the first experimental phase

4.1. Children's performance, age and routes

One of the indicators used to measure pupils' performance was the completely successful reproduction of each route. Success in this regard meant that the subject reached the end point after passing through the same decision points as they did when following the markers. The graph in Figure 4 shows pupils' performance (% success), according to age group (bars in shades of grey), for all routes travelled.

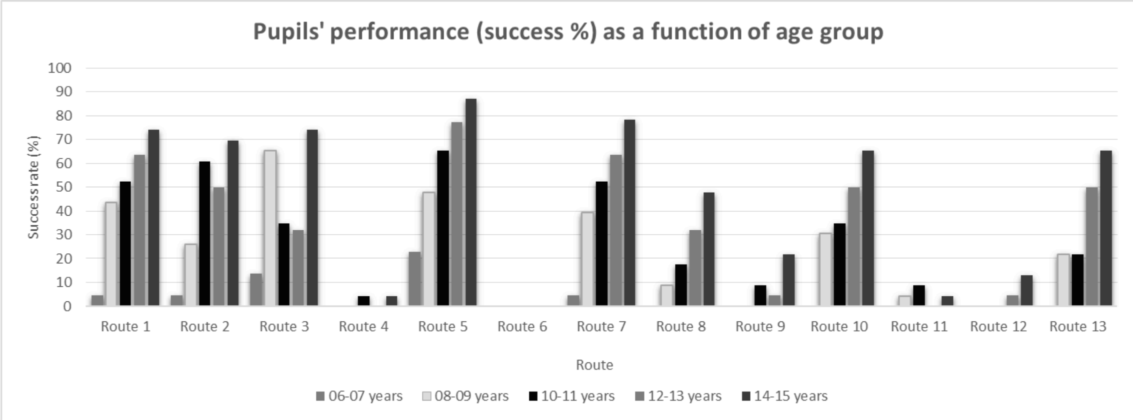

Figure 4. Successful performance of pupils (in %) as a function of age group for each of the routes travelled in V-Squarecity

As can be seen from the graph, the success rate is not the same for all routes. Routes 1, 2, 5, 7, 10 and 13 were generally more successfully completed than Routes 4, 6, 11 and 12. The presentation of the results according to age group also reveals a difference in success rates to the disadvantage of the younger subjects. Thus, for the majority of routes, the percentage of successes increased as the age of participants increased. Finally, it was noted that no subject succeeded in reproducing Route 6.

The graph suggests that there is no net learning effect, given that certain routes carried out at the end of the experiment were completed less successfully than the first routes set. The existence of an effect of weariness or fatigue cannot be excluded despite the fact that the final route (13) met with more success than Routes 11 and 12.

4.2. Influence of route length and number of inflection points

Before looking at the strategies used, it is interesting to consider the complexity of the routes set. It must be recalled that all the routes were of varying lengths (5, 7, 9 or 13 decision points (nDP)) and contained a varying number of changes of direction (1, 2, 4 or 5 inflection points (nIP)).

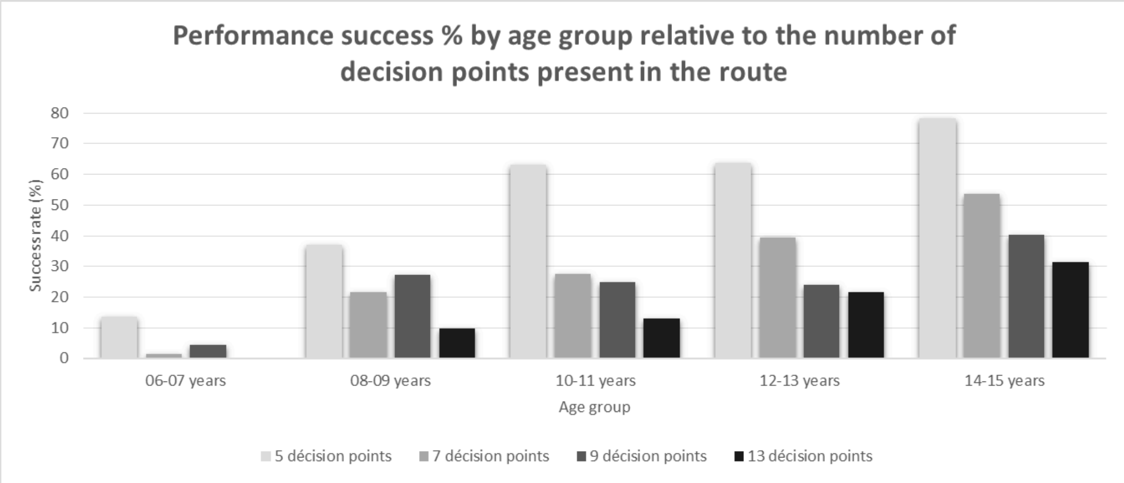

Figure 5. Successful pupil performances (in %) as a function of the route's number of decision points (nDP)

Whatever the age group, subjects were more successful on routes with five decision points than on routes with 7, 9 or 13 decision points (Figure 5). While this result is confirmed by the inferential statistics, significant differences appear in the performance between all routes ($\chi^2 = 13.208$; $P = 0.004$), and when the routes with 7, 9 and 13 decision points are taken into account, no significant performance differences can be discerned ($\chi^2 = 5.878$; $P = 0.053$, borderline significance). In other words, with the exception of the routes with five decision points, the length of the route has very little influence on pupils' performance in reproducing routes.

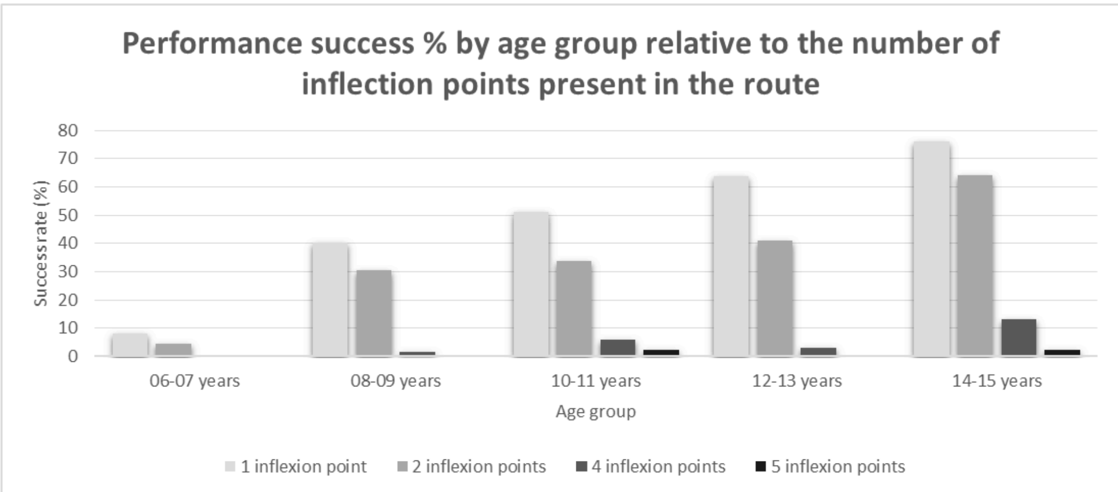

Figure 6. Successful pupil performances (in %) as a function of the route's number of inflection points (nIP)

Figure 6 shows the percentages of success by age group for routes with the same number of inflection points (1, 2, 4 and 5 inflection points shown in light grey, medium grey, dark grey and black respectively). Differences in route length are not taken into account.

As Figure 5 shows, regardless of the age group, subjects were more successful on routes containing one or two inflection points than on routes containing 4 or 5 inflection points. This result is confirmed by inferential statistics ($\chi^2 = 250.280$; P = .000).

The data gathered from recording the activity and performance of the children and adolescents reveal that, in V-Squarecity (Hippodamian type environment), changes of direction affect performance more than route length, provided the route has more than 5 decision points. With the exception of short routes, the performance of children and adolescents, whatever their age, is not as good when the route has more inflection points. There was more successful reproduction of routes with two inflection points than of routes with the same number of decision points but with four inflection points.

4.3. Strategies used and changes in preference with age

As Kitchin and Blades (2002) point out, our ability to navigate in an environment is based primarily on the ability of our brain to encode, organise, store, modify and retrieve spatial information. However, as mentioned earlier, it appears that this cognitive ability changes with age (Bohbot et al., 2012). Therefore, one objective of this research is to identify any development in the strategies used by children aged 6 to 15 when they are asked to reproduce a route in an unfamiliar environment.

The data (in percentages) obtained from the cognitive interviews are summarised in Table 3.

Table 3. Description of the strategies used by participants and presentation of percentages (%) by age group

	6 -7 years	8 -9 years	10 -11 years	12 -13 years	14 -15 years
Response strategy	59.1	47.8	30.4	18.2	13.0
Counting strategy	4.5	8.7	30.4	27.3	47.8
Mixed strategy (response strategy and counting strategy)	13.6	13.0	21.7	18.2	8.7
Use of a counting strategy and creation of mental maps	0.0	4.3	4.3	22.7	21.7
Use of response strategy and creation of mental maps	0.0	8.7	4.3	4.5	4.3
Memory of actions performed (kinaesthesia)	4.5	4.3	0.0	0.0	0.0
Creation of mental maps	0.0	0.0	0.0	0.0	4.3
Response strategy and memory of actions performed (kinaesthesia)	18.2	13.0	4.3	0.0	0.0
Counting strategy and memory of actions performed (kinaesthesia)	0.0	0.0	4.3	9.1	0.0
Total	100	100	100	100	100

These data show that, depending on the age of the subject, various strategies are used, based on:

- response strategy (use of landmarks),
- counting strategy,
- creation of mental maps,
- memory of actions performed (kinaesthesia)
- etc.

There are also mixed strategies that combine two or three of these approaches.

In order to report the results in an intelligible manner, the answers provided by the children and adolescents were grouped into three preference classes. The first was for use of landmarks. The second was for counting strategies, whereby teenagers organise and store spatial information in terms of number of steps taken or number of buildings passed and the direction taken (two steps straight ahead, turn left, three steps straight ahead, turn right) or in the form of chunks (2-G-D-3, etc.). The third class consisted of mixed strategies, for individuals without a preferred strategy and who both used landmarks and counted the number of blocks.

While more than 77% (77.3%) of pupils in the group of 6-7 year-olds said they used landmarks in order to carry out the exercise, only 69.6% of children aged 8-9 years old used them (Figure 7). This percentage falls to well below 50% for children aged 10-11 years old (39.1%) and decreases still further for adolescents aged 12-13 years old (22.7%). For the 14-15 year-olds, only 17.4% of adolescents were still using a strategy based on landmarks. For the second class, involving a counting strategy, the trend is reversed. Younger children make very little use of a counting strategy (4.5% for the 6-7 year-olds and 13% for the 8-9 year-olds), whereas 39.1% of children aged 10-11 counted the number of steps taken or the number of blocks (buildings). The percentage rises to over 50% for adolescents aged 12-13 (59.1%) and for adolescents aged 14-15 (69.6%). Concerning the third class, nearly 15% of all children and adolescents reported having no preference for a particular strategy and therefore used a mixed strategy. However, it is noticeable that pupils aged 10-11 made the most use of a mixed strategy (21.7%).

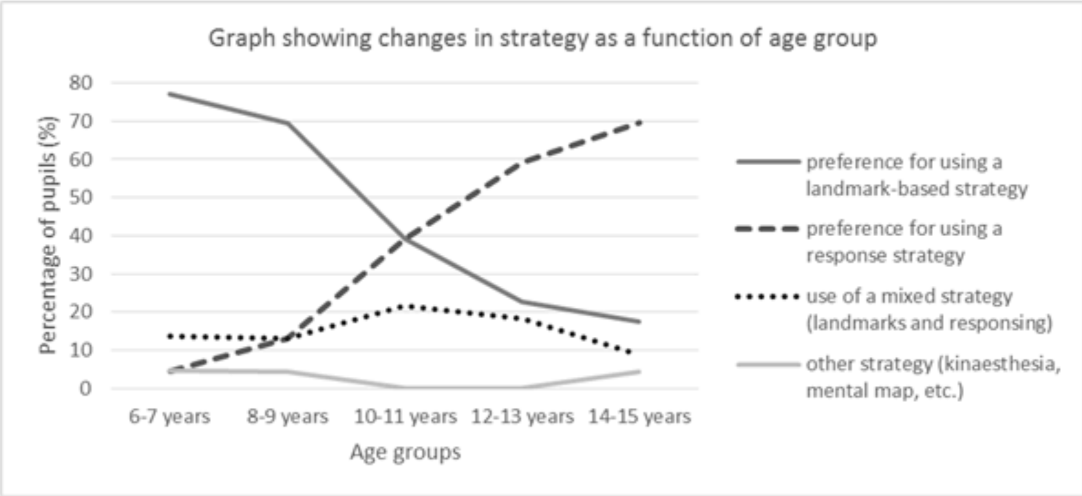

Figure 7. Graph showing changes in pupils' strategies as a function of age group

The data collected by recording the activity and performance of participants in the virtual environment confirmed that younger children tend to use a landmark-based strategy, whereas adolescents use a counting strategy. This can be illustrated by presenting the results obtained with routes with 9 decision points and 1, 2, 4 or 5 inflection points (Figure 8). As the markers were positioned randomly on different buildings, only the second route had landmarks at strategic locations, i.e. a coloured marker was present at each inflection point (T junction) and the end point. The three other routes (9 decision points and 1, 4 or 5 inflection points) were more successfully completed by pupils who used a counting strategy than by those who used landmarks. In the graph shown in Figure 7, it is notable that the route with markers (9 decision points and 2 inflection points) was more successfully completed by the younger children (65.2% success rate for those aged 8-9) than by the children aged 10-11 (34.8% success rate) or by the adolescents aged 12-13 (31.8%). The difference in performance between the age groups (8-9 years old, 10-11 years old, 12-13 years old and 14-15 years old) was confirmed as statistically significant ($\chi^2 = 20.115$; $P = 0.000$). The majority of older children also stated that they paid no attention to the markers.

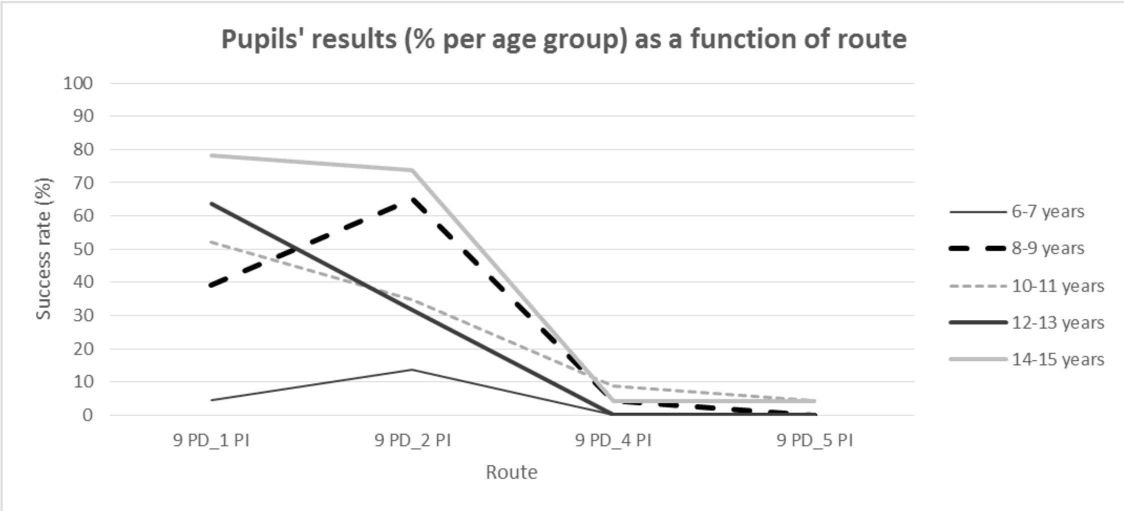

Figure 8. Pupil performance (% success rate by age group) as a function of the routes taken

Whereas the 10 and 11 year-olds used three different strategies (counting, response and mixed), the majority of adolescents aged 12 and above preferred to use a counting strategy.

5. Results of the second experimental phase, V-Squarecity vs V-Sinuouscity

Among the routes presented during the second experimental phase were two that had to be reproduced in V-Sinuouscity. These were routes with:

- 5 decision points and 2 inflection points
- 9 decision points and 4 inflection points

Routes with the same characteristics (number of decision points and inflection points) were also made in the V-Squarecity in order to be able to compare the results.

After each child had completed each route, a cognitive interview was conducted. During these interviews, 60% of children spontaneously commented that they had moved around in two different cities.

Table 4. Strategies that participants reported using in order to reproduce routes in V-Squarecity and V-Sinuouscity

Route	City	Response strategy	Counting strategy	Mixed strategy	Other strategies (Various)
5_2	V-Squarecity	7 (23.3%)	15 (50%)	6 (20%)	2 (6.7%)
	V-Sinuouscity	20 (66.7%)	4 (13.3%)	4 (13.3%)	2 (6.7%)
9_4	V-Squarecity	4 (13.3%)	13 (43.3%)	13 (43.3%)	0 (0%)
	V-Sinuouscity	15 (50%)	4 (13.3%)	6 (20%)	5 (16.7%)

The data from the cognitive interviews indicate the strategies that the subjects reported using in order to complete the routes in the two types of city (Table 4). For the route with five decision points and two inflection points (5_2), it was noted that in V-Squarecity, half of the subjects reported using a counting strategy, seven subjects reported using a response strategy, six subjects said they used a mixed strategy and two subjects used other strategies. For the same route in V-Sinuouscity, twenty subjects reported using a response strategy while eight said they used a counting or mixed strategy. Two subjects chose to use other strategies. For the route with 9 decision points and 4 inflection points (9_4) in V-Squarecity, two main strategies emerged: thirteen subjects reported using a counting strategy and another thirteen said they used a mixed strategy. Only four subjects reported using a response strategy. For this same route in V-Sinuouscity, fifteen subjects reported using a response strategy, six said they used a mixed strategy, five said they used other strategies (creation of mental maps, kinaesthetic support, etc.) and four subjects used a counting strategy. In order to confirm this, from the point of view of inferential statistics, the differences in percentages for the use of different strategies between the two cities and the chi-squares were calculated. For Route 5_2, there was a significant decrease in the use of a counting strategy compared to other strategies between the two cities ($\chi^2 = 9.320$; $P = 0.002$). For Route 9_4, a significant decrease was also found in the use of a counting strategy compared to other strategies between the two cities ($\chi^2 = 6.648$; $P = 0.010$).

6. Discussion, Conclusions and Implications for Future Research

Few studies have focused on how children and adolescents learn to memorise an itinerary (Nys et al., 2015) in a developmental perspective. In this article, the construction of spatial models of itineraries by children and adolescents, and the strategies they say they used to carry out the navigation exercises in different environments, has been discussed.

The authors' first hypothesis concerned the influence of the length of the route on success in route reproduction. The results presented here generally show a lack of effect for this variable. However, it should be noted that a very short route (5 decision points) cancels the effect of another variable, the number of inflection points. The results of the analysis of the number of inflection points as a variable reveals that this is a key factor in successful route reproduction. When there are fewer than two changes of direction, pupils' success rates are high, while with 4 or more inflection points the success rate falls, whatever the age of the pupil. At the end of the experiment, the second hypothesis can be confirmed, namely that increasing the number of changes of direction adversely affects the subjects' performance. The third and fourth hypotheses relate to how strategies change throughout childhood and the existence of a mixed strategy combining landmarks and counting, which can occur depending on the complexity of the environment and the level of development of the subject. While Bohbot et al. (2012) found that in a regular environment children prefer to use a response strategy (using landmarks), whereas young adults and older adults make more use of a counting strategy, this research has found that the change in strategy occurs around the age of 10 to 11 years old. According to experiments conducted, it was assumed that the preference strategy implemented by younger children is the identification of reference points or landmarks. That gradually changes into a sequence of movements (e.g. “go forward, go forward, go forward”). For older children, this succession of movement is summed up by aggregates of identical movements (e.g. “3x go forward”). To the two strategies identified by Bohbot and colleagues a third was added, which was called mixed. The existence of this mixed strategy, combining use of landmarks and counting, was revealed through the cognitive interviews. Finally, the data analysis leads to the conclusion that the exercises set in V-Squarecity (a regular environment) do not necessarily assess spatial abilities (strategies using landmarks), since teenagers use strategies based on organising and storing information in the form of chunks (Miller, 1956). This observation led to the development of V-Sinuouscity, a city presenting an irregular environment. It has been noted that subjects opted more for a landmark-based strategy in this city. The results thus confirm the fifth hypothesis, since the regularity or irregularity of the environment led to the development of different navigation strategies.

Given the difficulties inherent in field experiments conducted in a real-life context, a great deal of research into spatial cognition makes use of virtual reality. Multiple environments can be created to exercise and evaluate different spatial skills. In a regular environment, positions may be determined by a coordinated reference axis, by means of which the entire environment is encoded relative to the axes which define the grid. Subjects who realised that they were in this type of environment used counting strategies, in contrast with the other subjects, who used the landmarks provided by the environment. The period from 10 to 12 years old is a period of transition in the strategies used. Thus, up to the age of 10, children prefer to use response strategies, while from 12 onward, participants use accounting strategy. In between, at 10 to 11, some children use both strategies simultaneously. Although Bohbot and colleagues (2012) stressed that there is a change in strategy between childhood and adulthood, this research identifies the period during which this change in strategy occurs.

Knowing that in an irregular environment a coordinated reference framework is hard to find (Hart and Moore, 1973; Piaget and Inhelder, 1975, cited by Jansen-Osmann, Schmid and Heil, 2007a), a city based on a irregular plan was designed in order to encourage spatial orientation strategies rather than counting strategies or the use of coordinated reference frameworks. If the goal is to engage spatial skills (orientation, use of landmarks, exploration of environments, etc.) the use of fewer regular environments, in which counting strategies are relatively ineffective and landmark-based strategies have to be used, is recommended. On the other hand, if the objective is to assess the capacity to organise spatial information, regular environments can be used (Hamburger and Knauff, 2011).

The limitations of these two experiments can be identified, and they present new opportunities for research. The first concerns the way in which the instructions are given before the exercises are carried out. The fact that instructions are given before the marked routes are followed and the exercise carried out may lead subjects to develop a particular strategy. In the same vein, the second limitation is intrinsic to the activity requested, namely route reproduction. It is possible that the requested task itself induces a counting strategy on the part of the subject. If other activities were required in addition to the reproduction of routes (creation of maps, description of the landscape, etc.), this might have favoured counting less, and promoted the use of a different strategy. The intent is to use this approach in a future experiment involving decentration and transitivity. Finally, a last limitation may involve a possible learning or weariness/fatigue effect. Although no evidence of these two mechanisms was found, it would probably be useful to reproduce the two experiments varying the order of presentation of the situations.

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