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Intelligibility, cognitive mechanisms and visualisation of public space in map navigation.

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ABSTRACT

During goal-directed spatial navigation, cognitive mechanisms engage both an allocentric (planning) and egocentric (spatial updating) frame of references as one plans, makes decisions and moves through space. While the topological relationships measured in space syntax are allocentric in nature, the representations used, axial and segment maps, emphasise different spatial processes during map navigation related to the way public space is expressed. In addition, the figure-ground map, used as a basis for producing the axial map, provides information on the boundaries of the public space, the street width that can influence the choice of route.

The proposed navigational task entails drawing the shortest path between two diametrically opposed points on a series of circular maps using a digital pen and tablet, a technology used to measure minute variations in fine motor skills during graphical tasks. The same task is applied to two types of maps of the same urban areas: a street centerline map depicted by single black lines, an urban block map showing the boundaries of the public space by white space (figure-ground).

It is argued that during navigational tasks, the segment map, with its more fragmented representation of space, provides more insight on spatial updating associated with the egocentric frame of reference and the role of intersections; while the axial map, extracted from the block map, emphasising the presence of long straight lines, provides insight on the allocentric processing. Furthermore, the axial representation by embedding more hierarchical relationships seems to capture a more accurate experience of the public space more sensitive to variations in street widths, which lead to different choices of routes depending on the representation.

KEYWORDS

Intelligibility, Map representation, Segment map, Axial map, Map navigation

1 INTRODUCTION

Navigational tasks involve cognitive functions, motor efforts that are impacted by the nature of the environment. Urban environments have different levels of complexity in terms of street layouts, which impact their intelligibility: the regularity of a gridiron city provides a different set of references than those given by the meandering and narrow streets of medieval towns. However, finding one's way in a new urban environment often involves a series of steps such as knowing where you are, where you are going and how to get there (Golledge, 2003), especially in goal oriented navigation but may differ during open-ended exploration (Christova, Scoppa et al, 2012; Peponis, 2016). These processes are associated with cognitive efforts, as well as motor functions, that can be facilitated by spatial cues present in the environment. The presence of a landmark can help, for example, to orient oneself. When transposing navigational task to a two-dimensional representation of the urban environment, similar cognitive processes are taking place, but spatial cues visually differ. Motor functions can still be involved in the navigation process, either through eye's movement or of another limb such as the hand. Eye's movement can be involved in the planning part. Sakellaridi, Christova et al (2015) provide insights on how choices of location on a map are made based on eye's movement, demonstrating that the more time spent looking at an area, the most likely the location will be selected. The hand represents part of the spatial updating process involved during path tracing.

The cognitive functions involved in the navigation process are using two frames of references: "there is general understanding that in an egocentric reference frame, locations are represented with respect to the particular perspective of a perceiver, whereas an allocentric reference frame locates points within a framework external to the holder of the representation and independent of his or her position." (Klatzky, 1998, p.2). Cognitive maps involved in the decision-making process while navigating an urban environment are mental representation of spatial knowledge and help humans store and interpret spatial information in their mind (O'Keefe and Nadel, 1978; Kitchin, 1994). Cognitive maps imply hierarchy of spatial knowledge (Hirtle, 2003). They tend to be associated with the allocentric frame of reference by contrast to the egocentric frame of reference which is more related to route-based knowledge. Feedback from limb movements (motor function) are information that are associated with the egocentric frame of reference. They provide information such as speed, directions, and turns that are sequential as they are self-referenced and goal-oriented (Vorhees and Williams, 2014).

This paper looks at the relationships between configurational intelligibility of cities, decision-making during route selection and the cognitive and motor efforts of participants associated with such goal-oriented tasks. It suggests that different types of cartographic representations can help understand different aspects of the decision-making (cognitive function) that relates to map-based knowledge (allocentric) and route-based knowledge (egocentric) as both processes emphasise different aspects of spatial knowledge: allocentric is more hierarchical while egocentric is more sequential. The analysis looks first at the map-based strategy, establishing the impact of axial intelligibility on motor and cognitive functions. The route-based strategy is then analysed in more details to determine whether a relationship exists between the decision making and configurational and morphological properties of local elements.

2 REPRESENTATION AND NAVIGATION

This section presents the two-dimensional representations of public space in maps that provide and emphasize different features in order to assess the potential impact of these morphological and configurational characteristics on map navigation and route selection.

2.1 Representation of public space

Public space in many studies is represented and studied in its 2-dimensionality, where information about height and topography are removed. A figure-ground map emphasises the difference between built and unbuilt space (Rowe & Koetter, 1984), or in the block map, the difference between urban block – resulting from the aggregation of continuous plots, mostly private – and public space. Often derived from the urban block map, the street centerline map or segment map focuses essentially on the configuration of the public space, and even more so on the street network. Segment maps locate the route through a street half-way between the block boundaries. Difficulties arise in the depiction of public spaces that are not linear. For example, it is not easy to determine the configuration of the junction of segments at an intersection or how to translate a public square into a layout of lines. As a result, emphasis is put on the geometric properties (the angles for example). The axial line, also extracted from the block map, provides a different type of representation of that same public space by linking series of continuous spaces with a single element rather than depicting a specific route. Many axes can represent the same space. Furthermore, the axial map gives precedence to the longest axis over shorter ones, introducing hierarchy within the representation.

The block and segment maps foreground different characteristics of the public space. In the street centreline representation, all the streets have equal visual presence, as they all have equal width. The presence of intersections is clearer, and more systematic. In the block representation, the intersections are more loosely defined, and the presence of public squares and wider streets create a hierarchy in the street network not found in the centreline representation. The axial map representation generated from the block map embeds some of that hierarchy by first looking for the longest and fewest lines, favouring continuity through the wider and straighter axes. As such it appears that the axial map retains more of the hierarchical and global properties of the block map, while the segment map tends towards a more sequential and local representation.

From an analytical perspective, each map tends to favour a different unit of analysis. In the block map, the unit tends to be the urban block, and the public space is considered as the continuous left-over space with a complex boundary. Depicted as a continuous surface, it is difficult to analyse its properties. Marshall et al. (2018) provide a comparison of the different modes of representation of the street network and the biases embedded in each. From street surface, road centreline, axial line, continuity line to named street, their analysis of the public space concentrates on network modelling and their respective graphs models. This research concentrates on only two analytical representations, segment and axial maps, with respectively the segment (centerline between 2 intersections) and the axial line (longest line of sights) as units of analysis.

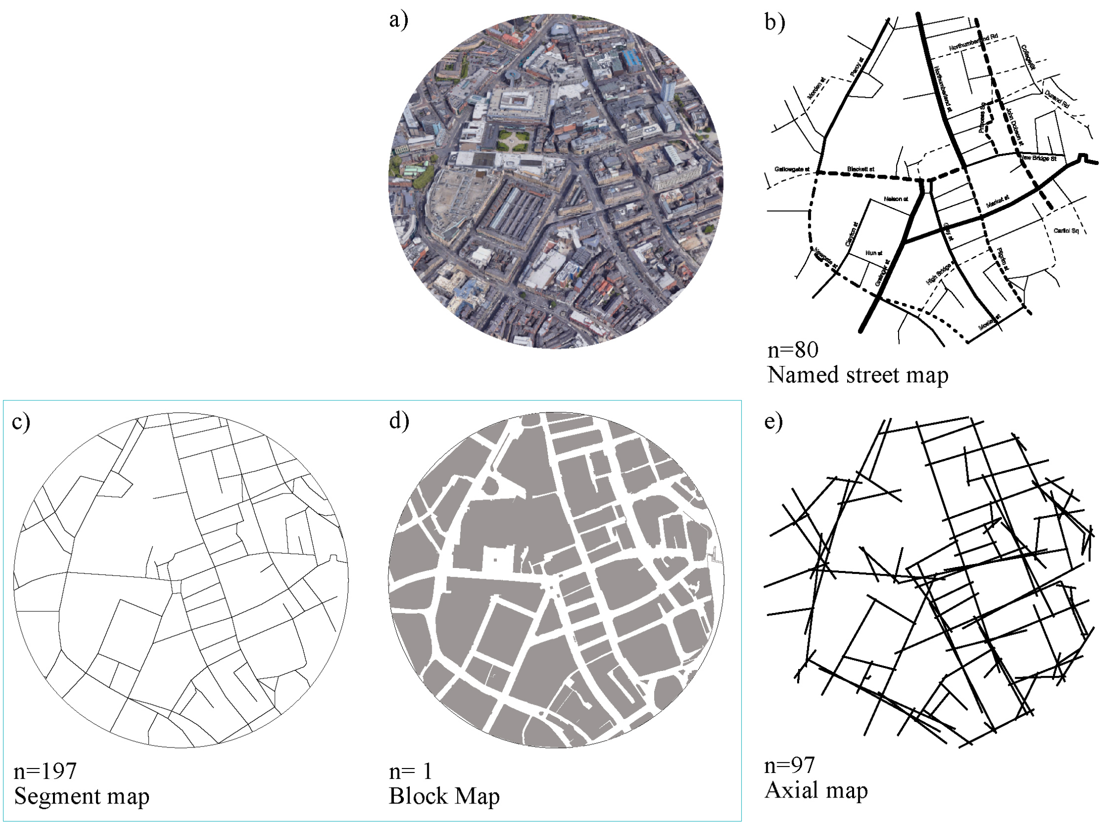

Figure 1: Various depictions of public space for an urban area: aerial view (google maps) (a), Named streets map (b), segment map (c), block map (d) and axial map (e).

Generally, there are fewer elements in the axial map compared to the segment map. In the example in figure 1, there are about twice as many segments as there are axial lines. They illustrate differences in how the map can be perceived. The number of named streets is closer to the number of axial lines rather than segments and take into account the same idea of continuity rather than fragmentation. Named streets map, like the axial map, embeds the notion of hierarchy visible in its nomenclature: road, street, lane, square… indicating local or global and formal characteristics (Tomko et al, 2008). A boulevard will have different characteristic and presence compared to an alley, etc…Morphological characteristics, such as the width, play an essential role in defining the street nomenclature and its hierarchy.

2.2 Navigation and choice/ decision

The type of representation might influence decision-making during navigation and wayfinding tasks as one takes cues from the environments. Golledge (1995) and Garling (2003) present a list of factors that can impact some of the route choices based on map navigation: shortest distance, least time, fewest turns, longest or shortest leg first, many curves or most turns… These factors describe the properties of the selected route and can be related back to the egocentric frame of reference. When tracing a route between two points on a map, decisions are made along the way that require spatial updating, at intersections for example when alternative routes are offered. As previously mentioned, route-based navigation is associated with sequential egocentric strategy that requires spatial updating, which underlying mechanism can be described as a series of vector summation. The segment representation, with many elements that highlight the presence of intersections, reduces it representations to a series of potential vectors. It can be hypothesised as more conducive and representative of the egocentric frame of reference.

Another study by Mohsenin and Svetsuk (2013) looks at the street properties that may impact cognitive maps or the allocentric perspective. They identify continuity, directional changes, street widths and well-defined street patterns, as potential factors. The block map provides an indication of street width and the axial map emphasizes this continuity and hierarchy (Hillier,Hanson 1984; Figueiredo et al, 2005). It can then be argued that they are more tuned towards the allocentric frame of reference.

3 DATASETS AND METHODS

A small study is designed to compare the two types of maps and assess their relationships with motor and cognitive functions.

3.1 Set up

20 participants are presented with two types of maps representing an urban area: a block map and a segment map. The map represents a circular area, a quarter mile radius wide, which corresponds to approximately a 5 min walk. Participants are asked to find and draw the shortest route between two points. No indication on how to interpret the shortest route is specified so as not to influence the choice of route. The points are located diametrically opposed at the periphery of the map. This task exemplifies the ease to traverse an urban environment, its intelligibility. The maps are presented on a digital support, a tablet, and the information are recorded by a digital pen, designed and used primarily as medical device for the detection of early signs of Parkinson's disease in a non-invasive manner (Tolonen et al., 2015). This technology provides

recording of minute changes in motion patterns (such as pressure and velocity) when performing a graphical task. The data recorded provide acute measures of motor skills associated with drawing. Positions along the path tracing are recorded by continuous sampling (200 Hz). Each position is associated to a set of coordinates (x and y), a timestamp, if the pen is touching (1) or hovering over the map (0). Further measures can be derived from this set of primary data set: total completion time, total distance, velocity, total vector angle… The way in which information are recorded in the device is very much sequential and record directional measures based on vectors. It is therefore more related to the egocentric frame of reference.

3.2 Measures

There are two sets of measures: one associated with the configurational and morphological properties of the maps and the other related to the performance of the participants to assess their cognitive and motor functions.

Configurational measures include *intelligibility* and *integration* for the axial map and a measure of choice – *normalised angular choice* [NACH] – for the segment map. *Axial Intelligibility* is determined by the relationship between the level of integration of the system as a whole - how accessible each space is from all the others - and the degree of connectivity it provides - the number of spaces directly available (Hillier, Burdett et al.,1987). An intelligible street network is when it is possible to get a sense of the system as a whole based on local information. It is argued that high correlation between the two properties indicates street systems that are cognitively easier to understand, and therefore to navigate. *Segment intelligibility* is calculated as the relationship between global properties (integration n) and local properties of the segment map (integration 3). *Choice* "measures how likely an axial line or a street segment it is to be passed through on all shortest routes from all spaces to all other spaces in the entire system" (Hillier et al., 1987, p.237). The spatial configuration of the street network is evaluated using Segment Angular Integration and *Normalised Angular Choice [NACH]*. It measures how many least angular paths lie between every pair of segments within a given distance taking different size of layouts into consideration. Intelligibility and NACH are calculated in Depthmap. While the navigation might be different in the two representations, the configurational measures based on both map representations, segment and axial, are allocentric in nature as they are calculated from all to all (Emo, 2014).

The morphological properties of public space in the block map are considered in the measure of street width. *Street width* is the average measure at the neighbourhood level (total street area/ total street segment length) and it is also provided every 2m by the length of the perpendicular to the street centreline between two urban block edges. This provides more continuous information as one moves from one space to another. This method of measuring street width is used as aggregated measure at the axial or segment level as an average value. Other local measures include the *number of intersections* per selected path in the segment maps, and the *number of axial lines* per selected path in the block maps.

Cognitive and motor functions are measures associated with the participants while navigating the maps. *Velocity* represents the speed of tracing based on the positions of the pen recorded at a frequency of 200hz during the task. From the same recording, *completion time*, *length* and *cumulative angle* of the traced routes can be derived. The cumulative angles of the drawn route partially measure tremor. It can be compared to the cumulative angles of the optimal path for the same route.

4 RESULTS

The Analysis is in two parts. The first section reports the relationship between morphological and configurational properties of the map as a whole on motor and cognitive functions. The second part looks more specifically at route choices (cognitive function) and different types of representations. The configurational properties of space as measured by axial line and segment analysis are further analysed to determine is a relationship can be established with motor and cognitive decisions.

4.1 Map level: Intelligibility and velocity

Two previous studies (Vialard 2020 and 2021) have suggested that a relationship between axial intelligibility and motor and cognitive function through velocity existed. They are combined and used to contextualise this present study. In all cases, the velocity value used is the average of multiple route selection recorded for multiple participants. However, the size of the sample of participants is not the same in the three studies, which might account for some of the differences. The setting of the experiment and the size of the maps are identical in all three studies, which allow for partial comparison of neighbourhoods.

Table 1. Overall intelligibility and mean velocity values when navigating block and segment maps.

City	Axial Intelligibility	Segment Intelligibility	Mean velocity (Block map)	Mean velocity (Segment map)
Agen	0.55	0.49	303	277
Amiens	0.80	0.64	402	354
Avignon	0.36	0.53	228	223
Clermont	0.54	0.47	268	257
Dijon	0.63	0.55	286	284
Tourcoing	0.78	0.66	349	325
Newcastle	0.54	0.54	213	196

Gangnam I	0.73	0.59	320	318
Gangnam II	0.51	0.53	269	320

Table 1 provides the values for a set of neighbourhoods showing different levels of axial intelligibility, with Amiens with the highest value ($adjR^2$=0.8) and Avignon with the lowest ($adjR^2$=0.46). The level of axial intelligibility for Newcastle city centre ($adjR^2$= 0.54) is comparable to the infill structure of one of Seoul superblock (Gangnam II, $adjR^2$= 0.51). The correlation between the mean velocity associated with the completion of multiple routes between two points on the block map and the level of axial intelligibility is the highest and most significant: $adjR^2$= 0.72, n=9, p=0.0024* (* denotes p <.05). The relationship between mean velocity while navigating the segment map and axial intelligibility is still meaningful but slightly weaker and less significant: $adjR^2$= 0.50, n=9, p=0.0198*.

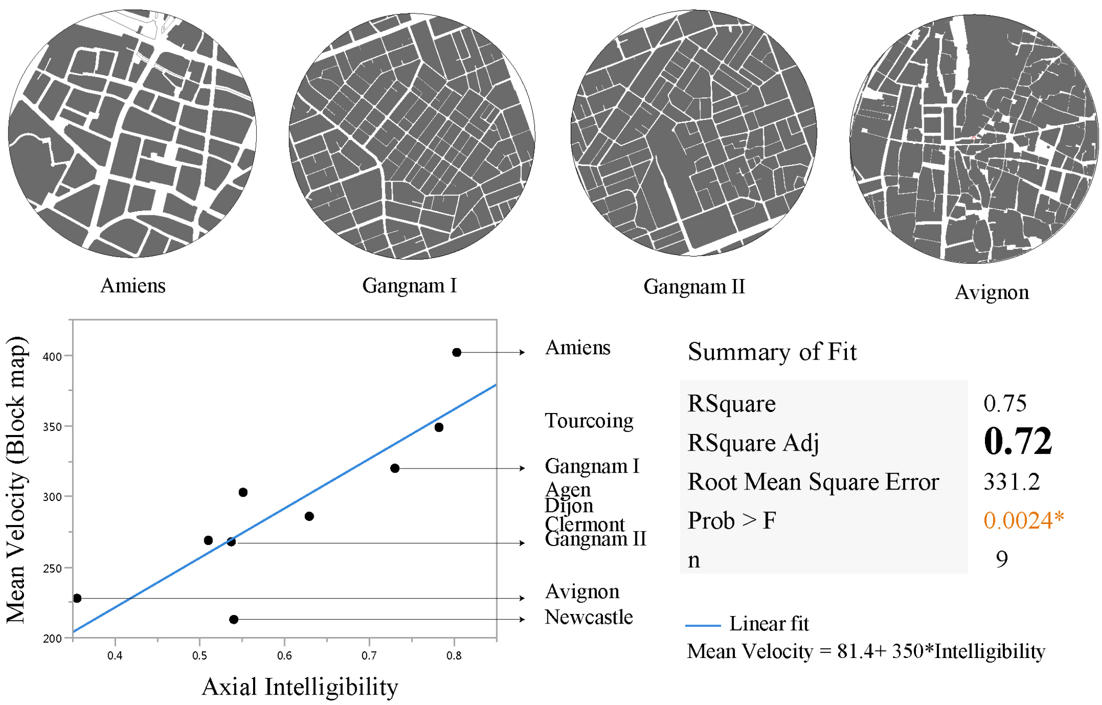

Figure 2. Linear fit between the measure of mean velocity of the navigation through the block map and axial intelligibility per city. The maps of Avignon and Amiens illustrate a respectively low and high intelligible structure. The two Gangnam maps shows two examples of super grid's infill.

When the same linear regressions are applied to segment intelligibility and mean velocity, there is a weaker and less significant relationship than in axial representation ($adjR^2$= 0.42, n=9, p=0.0353*) and even lower in segment representation ($adjR^2$= 0.29, n=9, p=0.0782).

These results support the previous finding that the configurational intelligibility of neighbourhoods impacts motor and cognitive functions. When neighbourhoods have more intelligible structure, they are easier to navigate. However, they also show that the relationship is stronger when measured by axial intelligibility. Moreover, the relationship of intelligibility with the speed of tracing differs depending on the type of representations, with the strongest relationship occurring when navigating block maps.

4.2 Routes characteristics

A comparison of route selections for both block and segment map is shown in figure 3 and the morphological and configurational characteristics are presented in table 2. It shows both the characteristics of the selected routes and their associated optimal path, how many times it has been selected and the motor and cognitive skills associated to their completion. In terms of mean total distance, completion time, cumulative angles and velocity, there seems to be no significant difference between the two modes of representation, although the optimal path is on average 9% longer in the segment map compared to the block map.

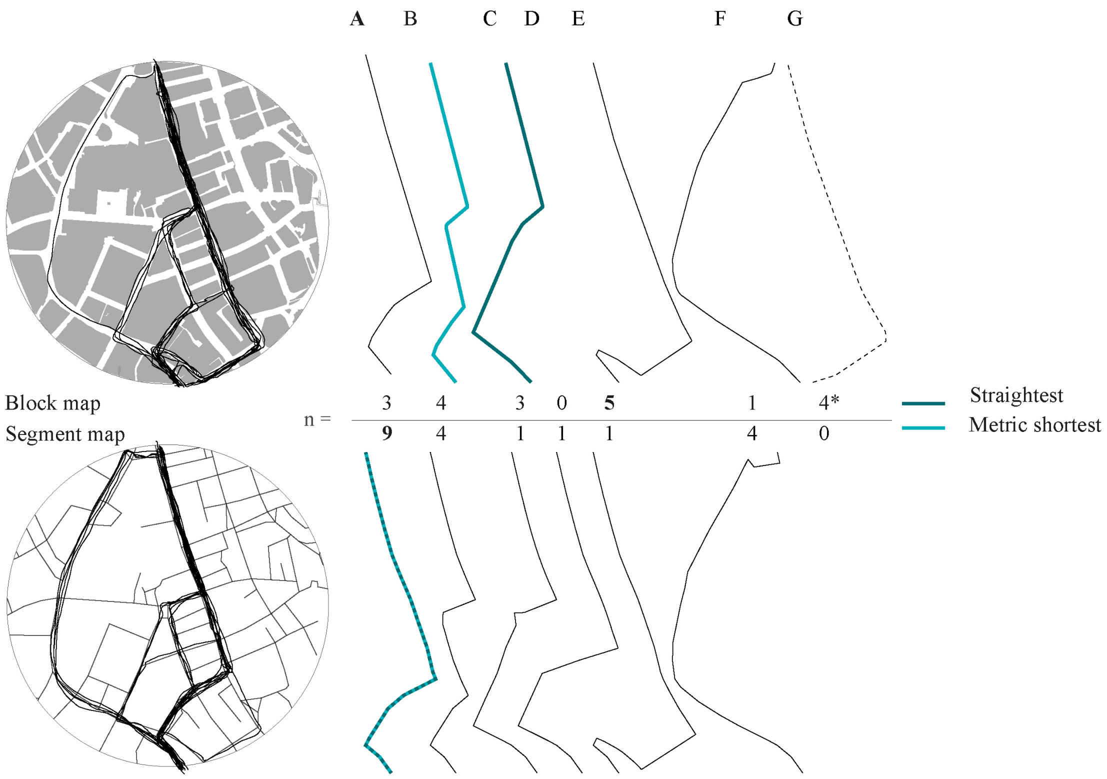

Figure 3: results of all the perceived "shortest" routes selected by the 20 participants for the two maps, and their equivalent paths and the number of times they have been selected in each type of maps.

Looking at path F, it looks like that in absence of width (segment map), the curved path is more attractive, although it is the longest in terms of distance (1.7% extra distance). Sevtsuk and Kalvo (2021) have found that in presence of alternative options, routes up to 20% longer could be selected, although they tended to be 9% longer on average. While it is only selected once in the block map, it has been selected 4 times in the segment map. Furthermore, in both representations, this is the path that is associated with the highest velocity (table 2), implying an easier navigation. Path G is not a true route as participants have drawn over a block rather than following the public space. However, if the selection of path G is combined with the one for path E, which is the same route but with the correct ending, they represent the primary choice with 45% of the selected routes for the block map. Both paths illustrate the tendency to follow the longest leg first and 'heading in the general direction' (Golledge, 1995). However, it is not true in the segment map, where the equivalent route is only selected once. This seems to suggest that the street width has visually a great impact on the selection of that specific route, creating a sense of continuity. Path A seems to be overall the path selected the most in the segment map (45%) and is indeed the shortest in terms of metric distance, in addition to being the straightest. If the two primarily selected paths are compared, they both start with the longest leg first, but their difference in the location of the turn toward the destination: the part of the path that differs is represented by a very narrow street in the block map (figure 1-d), which may have prevent its selection.

Table 2. Characteristics of the different routes selected on both maps.

	Optimal path									Routes (n=20)			
Type		Cumul. Angles	Length	Int [HH]/ NACH	n axial/ segments	Extra Ang	Extra Length	% selected (path)	Mean Width/ N intersections	Distance	Time	Cumul. Angle θ (tremor)	**Velocity**
Block map	A	176	916	2.15	4	0.4	3.4	15	16.2	1279	8.26	1285	**173**
	B	255	887	2.26	6	45.6	0.0	20	17.5	1272	8.98	1537	**161**
	C	176	932	2.39	4	0.0	5.1	15	19.2	1290	6.1	1073	**233**
	E	331	1124	1.98	6	88.9	26.8	25	17.2	1556	8.1	1712	**212**
	F	206	1051	2.01	5	17.3	18.5	5	21.1	1429	3.76	516	**380**
	G	119	957	2.33	3	-32.4	8.0	20	18.4	1253	8.48	1868	**181**
Segment map	A	241	948	1.24	21	0.0	0.0	45	19	1250	8.67	1601	**174**
	B	386	946	1.15	21	60.2	0.8	20	19	1294	7.04	1137	**186**
	C	379	1006	1.16	20	57.2	7.2	5	18	1250	6.66	979	**188**
	D	271	1062	1.22	21	12.6	13.1	5	18	1441	8.56	1961	**169**
	E	409	1170	1.18	28	69.7	24.7	5	23	1520	7.25	1312	**210**
	F	401	1112	1.10	21	66.5	18.5	20	17	1476	6.23	1030	**251**

To assess the role of the different morphological and configurational properties of a path on the likeliness to select specific routes, they are used to build a multi-regression model. The dependent variable is the percentage of how many times the route has been selected and the independent variables selected are: length, axial integration, number of axial lines (or changes of direction), and mean street width for the block map. While the regression coefficient is high ($adjR^2$= 0.65, n=6, p=0.3881), it returns a non-significant p value, which seems to indicate that there is not enough data to provide evidence of the relationships. The straightness of the optimal route (cumulative angles of the optimal path) has no effect in the model. For the segment map, the independent variables are: straightness of the path, length, NACH and number of intersections. The outcome is similar to the one of the axial map ($adjR^2$= 0.50, n=6, p=0.4568). Although the results are not significant, they seem to indicate that a relationship exists which would require further research and a more robust and extensive experiment.

5 CONCLUSIONS AND FURTHER CONSIDERATIONS

From the map-based perspective, this small study showed that high intelligibly urban areas are associated with faster navigation during goal-oriented tasks. Additionally, the measure of intelligibility which depicts properties of the overall structure of the map appears to be able to predict speed of navigation more strongly when measured from the axial map rather than the segment map. This relationship between intelligibility and motor function is reinforced when dealing with block maps rather than segment maps. Intelligibility provides insight into the structure of a neighbourhood as a whole, and as such can play an important part during the planning phase. To understand the impact of allocentric frame of reference (map reading) versus the egocentric frame of reference (path tracing), time could be allocated at the beginning of each task to allow for map reading, instead of allowing for direct tracing of the path. A comparison between the selected routes with or without planning time would provide additional information on the impact of cognitive mapping on map navigation.

From the route-based perspective, preliminary results seem to highlight different patterns of route selections depending on the type of maps. The two main observations concern the role of street width, which seems to lead to discarding very narrow streets in favour of seemingly continuous wide streets on the block map, and the difference in perception of the curvilinear path in both representations, which is more often selected when there is no width information. More research is needed to see if these findings will be still relevant for grid-like urban structure where choices of route are less differentiated (Mohsenin and Sevtsuk, 2013; Coutrot et al, 2020). A more extensive set of path selections from urban areas with different morphological and configurational properties will allow for clarification on the properties of selected routes.

While beginnings of relationships between motor and cognitive functions are established with configurational properties of maps, more work needs to be done to fully understand their complex relationship. The hypothesis was that block and axial map because of their hierarchical nature will be more correlated to factors facilitating allocentric navigation such as street width, selection of the longest lines and most integrated in the system. Another hand segment map was seen as more representative of egocentric navigation by association to spatial updating and should correlated with factors such as changes of direction and velocity. Some results seem to suggest that it is partially true, but a larger experiment including a wider variety of urban forms and participants is required to fully assess their impact.

In this paper, it is assumed that when analysing the configurational properties of an urban area, the axial map is more closely representative of the block map rather than the segment map, and serves as its proxy. This relationship between the block map and the axial map requires further study to fully assess the role of street width, and how well it is embedded in the axial representation. For this, the axial map deserves to be studied as an independent type of representation and then compared to the other two representations.

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