The influence of different cartographic materials on the cognitive processing of geographical time-space: an empirical study.

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***Abstract*— Geographers employ various techniques to represent the multiple dimensions of geographical time-space through maps. For example, precise cartographic transformations can be applied to distort spatial extents, enhancing the visualization of temporal distances. Some innovative cartographic representations, such as shrivelled maps, are specifically designed to depict time-space within transport networks where different speeds apply. Representing time-space in maps is a complex challenge, but it also raises questions about how such representations are interpreted and utilized by non-experts. In this study, we examined the impact of different geographic map formats on cognitive tasks requiring judgments of spatial distance or temporal duration in naïve participants. The behavioral results supported the hypothesis that different map formats exert distinct influences on the cognitive processes involved in these tasks. Additionally, the data suggested that shrivelled maps have the potential to facilitate the selection of optimal routes based on travel time, particularly in complex scenarios, given adequate training.**

Keywords*— *Spatial Cognition, Route Selection, Space and Time Perception, Cartography, Anamorphosis, Shrivelled Maps

I. Introduction

Humans, like most other animals, are capable of orienting themselves in space on the basis of empirical experience, by constructing mental representations to aid navigation [1]. It has been shown that the acquisition of spatial knowledge is highly dependent onour high-resolution visual system [2] and sensorimotor information related to self-motion [3]. These two types of information are not always available, especially when we consider very large spatial extents that cannot be explored directly and actively. This is the case forgeographical spaces, such as cities, regions or whole countries, which have to be grasped with the help of symbolic reductions such as maps [4].

For their everyday users, maps are analogical and have a truth value: apart from the absolute size of the places depicted, they are perceived as an exact depiction of spatial reality. However, to properly convey information, cartographers must select certain properties of space at the expense of others [5], making any cartographic representation inevitably incomplete and/or distorted. Most projection systems, the basic parameter of any cartography, introduce distortions in the relative distances between points [6]. Moreover, time is a more relevant measure than kilometric distance in explaining social behaviour [7]. This assertion has an even greater resonance in our modern condition [8], with faster transport systems [9], and where the mismatch between travel times and kilometric distances increases.

Since cartographic materials are essential for the acquisition of geographic spatial knowledge, cartographers' dilemmas have many implications for the psychological study of human spatial cognition. For instance, design choices concerning the representation of borders and boundaries on maps influence our perception of distances [10], due to the hierarchical nature of our understanding of space [11] and the limited cognitive resources at our disposal [12]. In some cases, the filtering and schematization of geographic information for communication purposes may also introduce cognitive biases that distort the geometry of spatial knowledge [13].

In this context, the effectiveness of different types of representations in supporting the construction of spatial knowledge at a geographical scale is a key concern for both geography and cognitive science. This issue becomes particularly critical when maps serve as tool for action—such as guiding mobility choices—where users must assess both spatial distances and temporal travel times. However, representing these two dimensions simultaneously is a challenge in itself: cartograms or anamorphoses distort straight line distances to reflect journey times, while traditional topographic maps, which represent exact spatial lengths, (aside from projection distortions), are unsuitable for conveying time-related information [14].

A solution has been proposed in the form of a three-dimensional cartographic model of time-space called the *shrivelled map* [15]. In this model, a transport network with multiple possible travel speeds is represented as an assembly of cones and transport links, where the length of each segment is strictly proportional to the duration of the trip. Like anamorphic plastic maps, shrivelled maps convey travel time information. Like conventional topographic maps, shrivelled maps can also encode information about kilometric distances, since all relative spatial positions of places are preserved in the top-view perspective. However, unlike these two traditional formats, shrivelled maps offer a more comprehensive model of time-space that could help users solve difficult route planning problems, such as space inversion [16].

Space inversion refers to a situation in which the coexistence of faster and slower speed infrastructures within the same network creates time-space discontinuities that complicate optimal route planning. In an extreme form of detour [17], the fastest route (in terms of travel time) may require moving away from the destination (in spatial terms) to access a faster infrastructure [7]. For individuals using maps to plan routes, space inversion is highly misleading since it triggers various route-planning heuristics or biases, often leading to incorrect decisions (e.g. *least-angle strategy*, [18]).

Due to its ability to jointly integrate space and time, particularly in the context of space inversion, the shrivelled map model may serve as an effective cartographic format for human route planning. The aim of this study is to experimentally assess how different cartographic formats influence map-based route comprehension and decision-making performance in healthy individuals. We expected the shrivelled map model to be a good alternative to traditional dimension-specialized map formats—the topographic and the anamorphosis models—for both spatial and temporal judgments while outperforming all models when optimal routes involve space inversion. To test these hypotheses, we asked participants to perform proximity judgements (task 1) and optimal route selection (task 2) for either dimension (spatial distances or temporal durations), on either a topographic map, and anamorphosis map, or a shrivelled map.

II. The Current Study: Methods

Participants 92 voluntary participants were recruited via a dedicated mailing list (mean age = 39.4, SD = 13.5, ♂ = 63%). No monetary compensation was provided for participation. All participants gave informed consent and data were strictly anonymized. All participants declared having normal or corrected-to-normal vision.

Material Items were cartographic materials displaying a fictional, simplified road network consisting of faster (red segments, 100 kph roads) and slower (yellow segments, 50 kph roads) speed infrastructures. Three map formats were created using Darcy, Shriveling world, Blender and Gimp softwares: conventional topographic maps (Fig. 1a), anamorphosis maps (Fig. 1b) and shrivelled maps (Fig. 1c). Each map displayed one (route selection task) or two (proximity judgment task) starting points, marked by a green circle and a green traffic light. The destination point was marked by a blue circle and a checkered flag. Possible routes were indicated by dotted or dashed lines superimposed on the network, labelled with the letters A or P. The shortest routes were determined based on GIS data, and maps were designed to ensure that the association between the shortest route, response side, response key, and overall map orientation was counterbalanced across participants.

Proximity judgment task Participants were presented with a map featuring two different possible starting points, each linked to a single destination point via unique routes. Their task was to determine which of the two routes was shorter, based on one of two dimensions: spatial kilometric distance or temporal duration (*two-alternatives forced choice*, see Fig. 1d for an example). For each trial, responses were given via keyboard input using the corresponding key (A or P), with no feedback provided. Correct answers and response times were recorded. The task included a training phase (8 trials) followed by a test phase (24 trials).

Route selection task Participants were shown a map with a single starting point and a single destination, connected by two possible routes. They were asked to select the shortest route based on either travel time, or kilometric distance (*two-alternatives forced choice*). Half of the items (maps) contained a space inversion: the shortest route (in terms of temporal duration) required initially moving away from the destination to access a faster infrastructure, making the longest route (in terms of kilometric distance) the quickest option (in terms of duration). Responses were also collected using the keyboard (A or P keys) with no feedback provided. The task consisted of a training phase (8 trials) and a test phase (24 trials), during which accuracy and responses times were recorded.

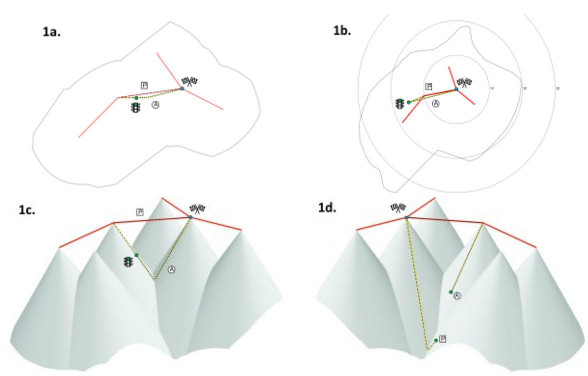

Fig. 1a: Example of a topographic map used for the route selection task. Fig. 1b: Example of an anamorphosis map used for the route selection task. Fig. 1c: Example of a shrivelled map used for the route selection task. Fig. 1d: Example of a shrivelled map used for the proximity judgment task

Procedure The experiment was conducted online using the Labvanced platform. After providing informed consent, participants were asked to calibrate the size of the experiment window by positioning themselves approximately 60 cm away from their screen ("arm length") and adjusting a visual guide to match the dimensions of a standardized chip card (e.g. a credit card). Screen resolution and size were computed from the calibration phase, and participants with a screen smaller than 30*18 cm were excluded from participating. Participantswere then informed that the experiment would last 30 minutes and require them to complete it without taking breaks, in a silent and isolated environment. After accepting these conditions, participants were pseudo-randomly assigned (with automatic sex counterbalancing) to one of three cartographic materials (topographic, anamorphosis or shrivelled). Each participant was exposed to only one map format (between-subject factor). Next, participants underwent a familiarisation phase, during which the reading principles of their assigned cartographic material was explained. They were informed that the maps represented an imaginary country where red paths corresponded to 100 kph roads and yellow paths to 50 kph roads. Concrete examples were provided (e.g. "*On this [anamorphosis] map, a town that is located 12 minutes away from the central point will be positioned slightly outside the first concentric circle ('10' minutes), regardless of its 'real' spatial distance in kilometers from the central point*"). Following the familiarisation phase, task order was balanced, with half of the participants beginning with the proximity judgment task and the other half starting with the route selection task. Participants were then presented with specific instructions for the corresponding task. Instructions included examples and explicitly stated that the shortest route for spatial distance would not always be the shortest for temporal duration, as some roads are limited to 100 kph and others to 50 kph. Instructions emphasized that the goal was to find the correct response as fast as possible, that travel times had to be estimated at a constant speed (without considering stops or slowdowns) and that the use of external tools was strictly prohibited. For each task, dimensions (spatial kilometric distance or temporal duration) were presented in separate blocks (balanced order) to prevent confusion between spatial distance and temporal duration judgments instructions. In the route selection task, the presence of a space inversion was randomized. Upon completing both tasks, participants were informed of the aims of the study and the experiment concluded.

Data analysis Response times exceeding10 seconds or below 500 ms were removed from the analysis to account for abnormally slow or fast trials, resulting in the removal of approximately 7% of individual trials. Response times for correct answers were then normalised using Tukey's ladder of powers [19] and analysed in this form using linear mixed model regression. Correct answers were analysed using generalized mixed model regression (GLMM) for binomial responses. For all measures and tasks, a forward model selection strategy was applied to find the best possible fit based on Akaike Information Criteria (AIC). For both measures and tasks, the best model consistently included all the two-way interaction effects between factors, except in the case of the response times model for the route selection task, which also included the three-way interaction between all factors. Experimental factors used as fixed effects in the linear mixed models were 1) cartographic material (topographic, anamorphosis and shrivelled), 2) dimension (spatial judgment or temporal judgement) and 3) **only for the route selection task,** space inversion (present or absent). Participants were included as random effect with random intercepts to account for individual variability. All models were tested for outliers using Cook's distance [20] and its corresponding implementation for binomial distributions. Post-hoc pairwise comparisons were conducted using the Bonferroni's comparison criterion [21]. Predicted probabilities of correct answer were extracted from the GLMM models by applying reverse logistic function to the estimated parameters. All analyses were performed using R software version 4.0.1 [22] utilising the lme4 package [23] and the emmeans package [24]. We used 0.05 as significance thresholds. Due to length constraints, only the most relevant results related to the previously stated hypotheses will be reported in this paper.

III. THE CURRENT STUDY: RESULTS

a. Proximity judgment task – correct responses

Statistical analyses revealed a significant main effect of cartographic material, with mean correct answers to the topographic map (M = 0.8, SD = 0.39) being higher than the anamorphic map (M = 0.65, SD = 0.48 ; β = -4.29, z = -9.42, p <0.001) and the shrivelled map (M = 0.54, SD = 0.49 ; β = -5.2, z = -11.3, p <0.001). A main effect of spatial dimension was also found, indicating that, in average, correct responses were more frequent when estimating temporal durations (M = 0.77, SD = 0.43) than spatial distances (M = 0.57, SD = 0.49; β = -3.47, z = -9.52, p <0.001). However, a significant interaction effect between cartographic material and dimension revealed that this effect was reversed depending on the cartographic material when comparing topographic maps to anamorphoses (β = 6.06, z = 14.54, p <0.001) or shrivelled maps (β = 6.13, z = 13.75, p <0.001). Post-hoc pairwise comparisons revealed that topographic maps led to better performance when estimating spatial distances (z.ratio = -9.52, p <0.001), while anamorphoses (z.ratio = 10.87, p <0.001) and shrivelled maps (z.ratio = 13.3, p <0.001) yielded better performance when temporal durations had to be estimated. In addition, the predicted probabilities for the poorly performed dimensions on each cartographic material were around 50% (temporal durations on topographic maps = 0.65%; spatial distances on anamorphoses = 0.47), except for the spatial distances for shrivelled which was 25.9% (see Fig. 2). Post-hoc analyses confirmed that the difference between spatial distances on topographic maps and shrivelled maps was significant (z.ratio = -5.22, p <0.001), but that the difference between spatial distances on shrivelled maps and on anamorphoses was just slightly tendancial (z.ratio = 2.8, p = 0.059).

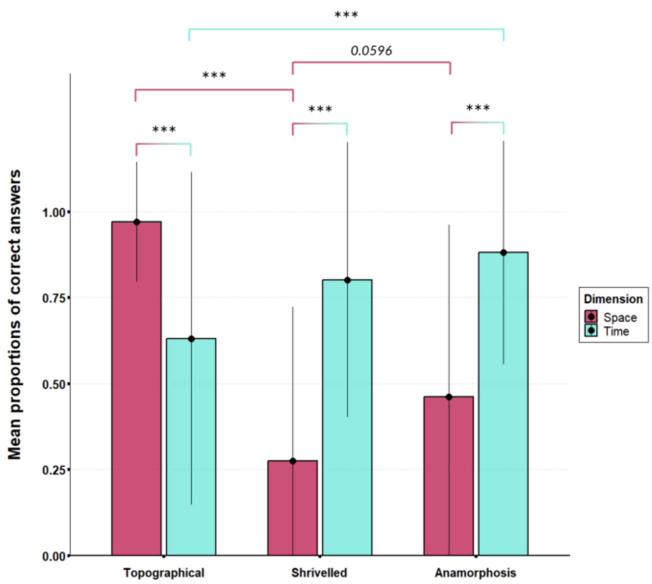

Fig. 2: Mean proportions of correct answers to the proximity judgment task by cartographic material and dimension (Error bars show standard deviations)

b. Proximity judgment task – response times

Response times were significantly faster for topographic maps (M = 3.19 sec, SD = 1.67 sec) than for anamorphoses (M = 3.45 sec, SD = 1.65 sec; β = 0.12, t = 3.00, p = 0.003) and for shrivelled maps (M = 3.94 ms, SD = 2.02 ms ; β = 0.24, t = 5.55, p < 0.001). As for correct answers, while a significant main effect of dimension was observed (β = 0.09, t = 6.37, p < 0.001). Interaction terms revealed that this effect was reversed for anamorphoses (β = -0.17, t = -7.462, p < 0.001) and shrivelled maps (β = -0.24, t = -9.12, p < 0.001). Post-hoc analyses therefore showed that participants were slower at estimating temporal durations (compared to spatial distances) on topographic maps (t.ratio = 6.37, p <0.001), but faster to do so on anamorphoses (t.ratio = -4.2, p <0.001) and on shrivelled maps (t.ratio = -6.72, p <0.001 ; see Fig. 3).

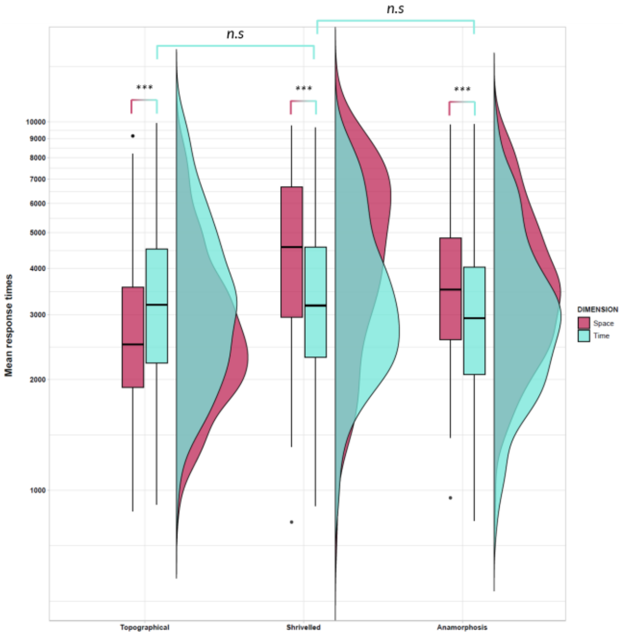

Fig. 3: Distributions of response times (on a logarithmic scale) to the route selection task by cartographic material and dimension. (Error bars show standard deviations)

c. Route selection task WITH space inversion

Results showed that while overall performance for the route selection task was worse with space inversion (β = -7.23, z = -11.8, p <0.001), significant interactions with dimension (β = 8.13, z = 14.45, p <0.001) and the shrivelling map (β = 3.51, z = 6.78, p <0.001) were found. More precisely, contrast analyses showed that, when space inversion was present, shrivelled maps (predicted probability = 0.96%) outperformed topographic maps (z.ratio = 4.58, p <0.001) and anamorphoses (z.ratio = -3.57, p = 0.018) for temporal durations estimations. Nevertheless, when space inversion was present, spatial distances were systematically biased toward the incorrect choice for shrivelled maps (predicted probability = 0.16%) compared to topographic maps (z.ratio = -10.76, p <0.001) or anamorphoses (z.ratio = 10.15, p <0.001; see Fig. 4).

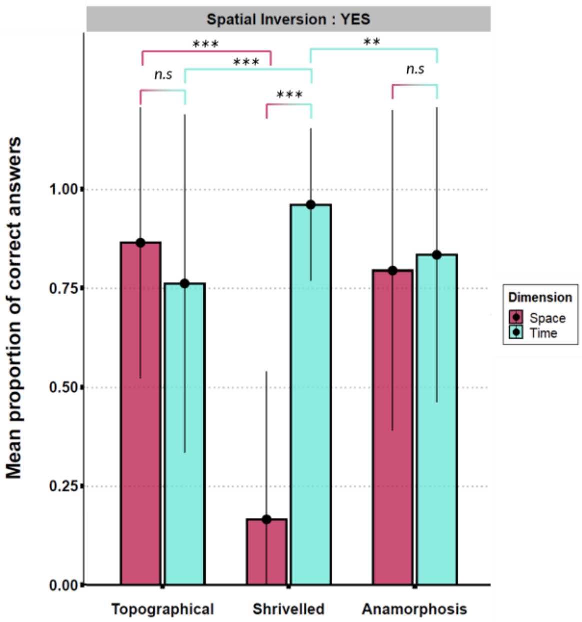

Fig. 4: Mean proportions of correct answers to the route selection task by cartographic material and dimension, only for space inversion trials (Error bars show standard deviations)

IV. Discussion and perspectives

The aim of this study was to investigate how different cartographic materials influence spatiotemporal judgments and route selection. We hypothesised that classical map formats, which specialize in representing a single dimension (respectively, spatial distances for topographic maps and temporal durations for anamorphoses) would facilitate the processing of the corresponding information in both route selection and proximity judgments tasks. This expected congruency effect between the type of map representation and the type of information processed was confirmed: topographic maps led to better performances for spatial kilometric length judgments across both tasks, while anamorphoses improved performances in temporal duration judgments. this Furthermore, this map-dimension congruency also facilitated cognitive processing by reducing response times, suggesting that effectively lowers extraneous cognitive load associated with the use of cartographic designs [12].

The second goal of this study was to test the novel hypothesis that shrivelled maps, a theoretical model of geographical time-space, could be effectively used by humans to solve cognitive tasks. Specifically, we expected shrivelled maps to serve as a suitable representation for both temporal durations and spatial distances judgments. The fact that shriveled maps happened to be a good intermediate solution in terms of performance for temporal durations estimations in the proximity judgment task validated this hypothesis. However, contrary to our expectations, this was not the case for spatial distances judgments. In fact, correct response percentage for the spatial dimension on shrivelled maps were systematically lower than on any other cartographic material. While this could suggest that shriveled maps are simply not suitable for estimating kilometric distances, the results specifically showed a bias towards the wrong answer in this condition. This is unexpected because, as seen in non-congruent trials for topographic maps and anamorphoses, spatial estimations should have approximated chance level in that case (50% accuracy). This crucial finding shows instead that shrivelled maps inherently encourage a preference for time-optimized routes, even when spatial distance is the relevant decision factor.

One key property of shrivelled maps is that kilometric distances are preserved when viewed from a perfectly vertical perspective or when the lengths of slow-speed segments (yellow routes) are divided by two, as in our specific examples. However, these decoding principles were not explicitly communicated to participants in this study. Consequently, it is likely that the familiarization process was not thorough enough to enable effective use for estimating kilometric distances. This assumption is supported by the response time analysis, which revealed that participants took significantly longer to estimate kilometric distances than temporal durations when using shriveled maps. Since response times can serve as an indicator of additional cognitive processing demands, including potential mental imagery [25] , these findings suggest that participants had to engage in extra cognitive computations to interpret spatial distances correctly. For the shriveled model to be effectively usable by everyday users, it must be made more intelligible through explicit decoding instructions, thereby reducing the cognitive load associated with these additional computations.

To address this, an ongoing study has been designed to provide better familiarization with the shriveled model and test this hypothesis.

The final objective of the study presented here was to test the hypothesis that shrivelled maps could assist users in solving the specific route selection case of space inversion. Space inversion requires travelling more spatial distance, more detour, initially heading in the opposite direction of trip destination, to optimize temporal duration. We therefore expected participants to struggle with estimating optimal temporal durations in space inversion scenarios, except when using the shrivelled map, which provides a clear visual representation of time savings associated with faster infrastructures. Notably, performances in this condition were not as poor as anticipated for topographic and anamorphoses maps, suggesting that the task may have been too easy. Nevertheless, our results clearly demonstrate a facilitating effect of the shrivelled map on temporal estimations with space inversion compared to all other cartographic materials. This novel finding suggests that the integrated time-space representation offered by shrivelled maps could be valuable for designing innovative schematic maps tailored to route planning in multi-speed networks. While future research should further investigate their effectiveness in conveying both spatial distances and temporal durations, another promising avenue would be to explore user's declarative preferences for this type of design [26]. This could provide insights on how shrivelled maps might contribute to applied fields such as human mobility.

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