Collaborative Wayfinding Under Distributed Spatial Knowledge

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Abstract

In many everyday situations, two or more people navigate collaboratively but their spatial knowledge does not necessarily overlap. However, most research to date, has investigated social wayfinding under either 1-sided or fully shared spatial information. Here, we present the pilot experiment of a novel, computerised, non-verbal experimental paradigm to study collaborative wayfinding under the face of spatial information uncertainty. Participants (N=32) learned two different neighbourhoods individually, and then navigated together as dyads (D=16), from one neighbourhood to the other. Our pilot results reveal that overall participants share navigational control, but are in control more when the task leads them to a familiar destination. We discuss the effects of spatial ability and motivation to lead, as well as the outlook of the paradigm.

2012 ACM Subject Classification Applied computing → Psychology; General and reference → Experimentation; General and reference → Empirical studies

Keywords and phrases navigation, wayfinding, collaboration, dyad, online

Digital Object Identifier 10.4230/LIPIcs.COSIT.2022.25

Category Short Paper

Funding The research was partly conducted at the Future Cities Laboratory at the Singapore-ETH Centre, which was established collaboratively between ETH Zurich and the National Research Foundation Singapore (NRF) under its Campus for Research Excellence and Technological Enterprise (CREATE) programme. The research was also supported by the Chair of Cognitive Science, ETH Zürich. S. Kuliga at the time of preparing the study held a DAAD Postdoc Fellowship at Singapore-ETH Centre and currently is affiliated at DZNE Witten / University of Witten/Herdecke.

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15th International Conference on Spatial Information Theory (COSIT 2022).
Editors: Toru Ishikawa, Sara Irina Fabrikant, and Stephan Winter; Article No. 25; pp. 25:1–25:10
LIPICS Leibniz International Proceedings in Informatics
Schloss Dagstuhl – Leibniz-Zentrum für Informatik, Dagstuhl Publishing, Germany

Acknowledgements We are grateful for the advice of Dr Iva Barisic on social wayfinding, and the support of the ETH Zürich Decision Science Lab team: Stefan Wehrli, Lea Imhof, and Salome Egli.

1 Introduction

In everyday life, we often navigate together with other people, a process called "social wayfinding". In some cases, we may share similar environmental knowledge, for instance while walking together with a friend around an area we both live in. In other cases, we may have different environmental knowledge than the other person. We define this as *spatial information uncertainty*, where two (or more) people have non-overlapping, complementary spatial knowledge – in other words, each of them only knows parts of the area to be navigated. This is the case, for example when guiding a taxi driver how to find our home, which we need to communicate to them. This phenomenon is called "social wayfinding" [5], and here we focus on the *synchronous/strong* type of social interaction. This is the case of pilot and co-pilot in air-crafts, driver and passenger cars, and of course pedestrians. In such cases, the interpersonal dynamics between then two or more individuals influence both the nature of their interactions as well as their wayfinding performance and outcome.

Previous studies have shown a clear influence of personality traits (spatial ability, leadership tendencies) of each individual, the spatial information available, and the wayfinding agency (who is in command of the steering wheel). Passengers in a car who consider themselves as having a better wayfinding ability than the driver, they are more likely to support the driver (collaborate) providing input for tasks such as pre-planning, en-route wayfinding directions or visual search [3]. Groups of people take more time than individuals to complete the same navigational task [2]. Imbalance of spatial ability in navigating dyads may lead to additional communication and dissatisfaction [6]. Males tend to assume more control in mixed-sex dyads [8]. Groups varied in leadership, some having a navigational leader and others not; this was explained by an overall level of *conscientiousness* of the dyad; however within the dyad *conscientiousness* was not related with leading [1]. Navigational control has been related with individuals' leadership tendencies [2], a construct called *motivation to lead* (MTL) [4]. However, unlike individual-navigation, currently there is not an experiment paradigm to study collaborative navigation in a controlled or networked manner. In addition, in previous studies the navigators (dyads or teams) either all or only one had access to the same amount of information (e.g. a map). Thus, it is not known how people would collaborate if they have known different parts of the environment.

In this pilot study, we investigate these two questions: a) how to study collaborative navigation using a computer-based paradigm, and b) how dyads collaborate under spatial information uncertainty. Specifically, we implement a computerised, non-verbal collaborative navigation paradigm to explore: which player of each dyad assumes more navigation control during a wayfinding trial (RQ1); how taking navigation control is moderated by individual characteristics, i.e., sense of direction and motivation to lead (RQ2); and which strategies individuals use in collaborative navigation (RQ3).

2 Methods

2.1 Participants

Thirty-two participants (N = 32, 17 female; mean age = 23.7 years old) took part in this pilot study, and two (2) more dropped-out due to motion-sickness. They were recruited from the Decision Science Laboratory of ETH Zürich (DeSciL) participant pool, and testing took

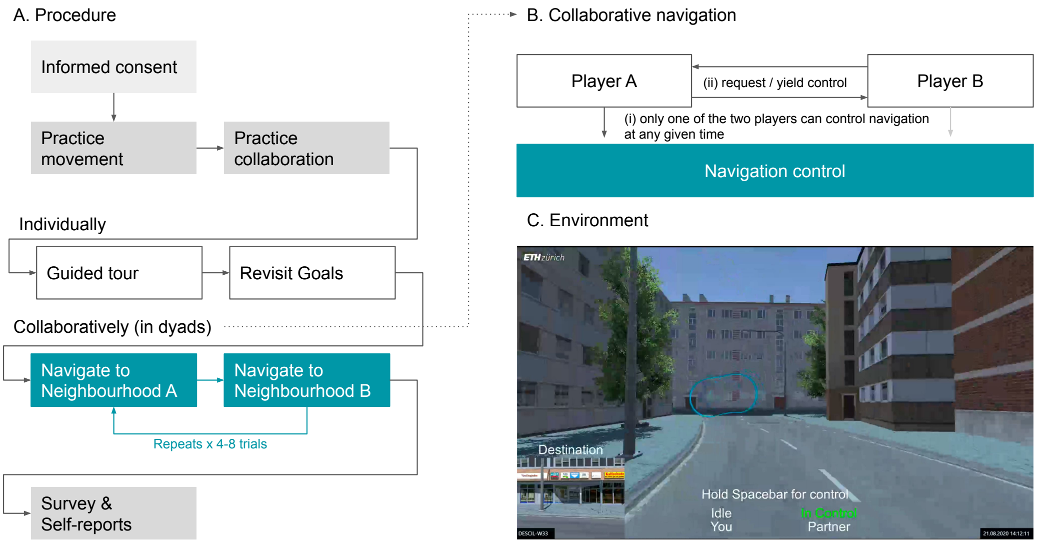

Figure 1 (A) Experimental procedure. (B) Only one of the two players in the dyad is in control of the navigation at any point in time (i), and the other player can request control. (C) Example screenshot of the environment during one navigation task. Goal locations remain visible during the entire task. Participants can always see who is in control. Also note that communication is non-verbal and the only message participants exchange is to request navigation control.

place in DeScil which allows simultaneous data collection during a single session. Participants were compensated 25 Swiss Francs (approximately 26 US$). The study was approved by the ETH Ethics Committee (Project ID: B EK 2019-N-179). All procedures were performed according to the declaration of Helsinki.

2.2 Experimental design

For this pilot study, we adopted single factorial repeated measures design, with a single factor: spatial knowledge of the starting area or the goal area. Specifically, participants learned individually to navigate to 6 locations in one out of two neighbourhoods of a small virtual city (cf. 2.4 and appendix). Subsequently, they were assigned to dyads of distributed spatial knowledge – in other words participants were paired up by the researcher, so that if one participants learned neighbourhood A, the other learned neighbourhood B. We explored whether spatial ability, personality (motivation to lead) or spatial knowledge determined which participant was in charge of navigation during the wayfinding tasks, and also explored their strategies.

2.3 Procedure

Participants were received at DeScil, briefed by the experimenter, and provided consent. They received instruction and practise time on how to look around, navigate, obtain and yield control of the navigation interface.

Training Phase. During this phase, participants were randomly assigned to a neighbourhood (A or B) and they learned individually the location of six (6) goal locations in their assigned neighbourhood (A or B) through a guided tour (passive learning). Afterwards, to assess the quality of their spatial learning, they were immediately teleported to the start of the tour, and asked to revisit all six goal locations again, navigating independently. After revisiting all goals, they could continue exploring their assigned neighbourhood; note that they could not cross or see their partner's neighbourhood or any large distal landmarks.

Testing phase. Participants were paired in dyads (one from A and one from B). Navigating dyads were asked to complete a series of wayfinding tasks (4 trial for pilot session 1 and 2; 8 tasks for pilot session 3). They were explicitly told they were paired with another partner, and shown how to get and give control. In each trial, the dyad was teleported to a location in one neighbourhood and asked to "find the shortest path" to a location in the other. Each player was sitting on separate monitors and could not see who their partner is. Only one of pair could be in control of the navigation at any given time. The player *not* in control could request control with a simple message (initiated by pressing a button); no other form of communication was allowed.

2.4 Environment and Data logging

Figure 1 C shows an image from the testing environment which was also created in Unity 3D (Unity Technologies, USA). The virtual city was split in two neighbourhoods of approximately similar area and number of streets (see also Figure 4 in the Appendix). Because the two neighbourhoods have similar visual appearance, we enhanced their differentiation with two additional visual cues: one neighbourhood had red and the other blue paving, while one had trees and the other not. Six locations distributed across the entire area of each of the two neighbourhoods were used as goals / destination (12 in total). These included, for example, a fountain, a gas-station, and various shops. The two virtual neighbourhoods were located next to each other, with connecting streets. Testing collaborative navigation in a network virtual setup allows the precise control of environment conditions and confounds, as well as provides a scalable paradigm for spatial cognition research.

Both the experiment procedure and data collection were implemented in Unity 3D, relying on the *UNet* framework (now deprecated) to enable multiplayer sessions. During the (pilot) experiment, behavioural data were recorded at a sampling rate 5Hz, including: the coordinates (x,y,z) of the player (during training) or the dyad (during testing), which player out of the two was in control, as well as the stage of the experiment (training or testing), task order, and other auxiliary data (computer id).

3 Behavioural and self-reported measures

Training performance. Defined as the (virtual) distance travelled to revisit all six landmarks a participant learned during the guided tour. This produced one value per participant.

Testing performance. Defined as the (virtual) distance travelled while performing the dyadic navigation tasks. This produced one value per dyad (for each trial).

Total proportion in control of navigation. Defined as the proportion (measured as number of logs/rows) that each player was in control of the navigation during each task. This produced one value per participant (for each trial).

Proportion in control of navigation per area. Defined as the proportion (measured as number of logs/rows) that each player was in control of the navigation during each task, *and* within each of the two regions. This captured how much a player was in control in the area they had learned versus the unknown area. This produced two values per participant (for each trial).

This data were joined with two standardised questionnaires measuring the self-reported sense of direction (spatial ability) and motivation to lead. We used the Santa Barbara Sense of Direction (SBSOD) to assess participants' self-reported spatial ability [7], which consists of

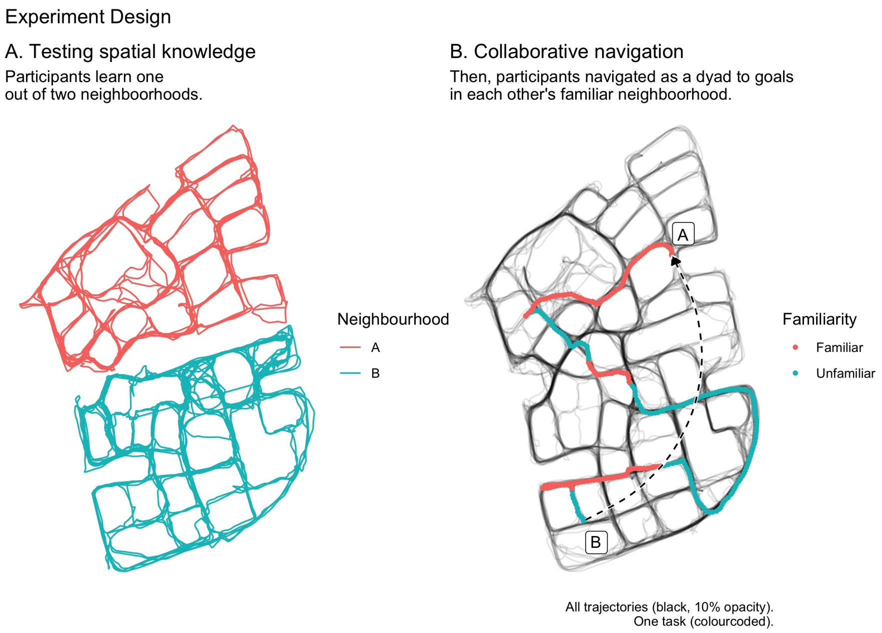

Figure 2 Maps of key behavioural data from wayfinding during the individual training phase (landmark revisit task; left) and the testing phase (dyadic navigation; right). Notice that each participant learns one out of the two neighbourhoods (A or B). They thus have different spatial knowledge of a region. Subsequently, each collaborative wayfinding trial starts in one neighbourhood and ends in the other; thus during the navigation phase, players alternate between being in a familiar environment. We can notice that Player A (unfamiliar with neighbourhood B) started navigating first, before handing over control to Player B (familiar); the pair kept exchanging navigating; eventually Player A (familiar with with neighbourhood A) led them to the destination.

15 items such as “I am very good at giving directions”, rated in a 7-point scale. We also used the *motivation to lead* (MTL) scale [4], which includes 27 statements, such as “I usually want to be the leader in the groups I work in”, that belong in 3 separate factors (see Introduction).

3.1 Data pre-processing and Analysis

Overall, during 3 pilot sessions with 32 participants we obtained a total of 247,549 rows of data, consisting of training and testing data from both participants of each data (i.e. data logs are recorded on both sides of a dyad for redundancy). During the pre-processing step, the data were split into training phase (i) guided tour and (ii) goal revisit, and testing phase (iii) the dyadic navigation tasks. Based on these data, we computed the behavioural measures defined above. All data processing and analyses were performed in R (see Appendix for list of packages used).

4 Results

4.1 Manipulation check

As an initial test of our experimental paradigm, participants self-reported that they understood the task and interface (see Figure 6 in the Appendix). The majority (75%) also reported that they realised if they were teleported to their “own” (i.e. familiar) or the “other” neighbourhood at the beginning of each trial, although almost half did not notice the visual cues (i.e. trees and pavement colour).

4.2 Spatial learning

As an initial test of how well players learned the environments, we examined their training performance. Note that this was only recorded for pilot session 3 (12/32 participants). Overall, participants varied in their goal-revisit performance, and a bayesian correlation test revealed anecdotal evidence (BF = 1.14) that it was inversely correlated with Sense of Direction ability (Rho: -0.28; 95%Cr.I. = [-0.6, 0.08], probability of direction = 0.87).

4.3 Collaborative navigation

Examining the research questions, we first explored which player of each dyad assumed more navigation control during a wayfinding trial (RQ1). A bayesian ANOVA revealed evidence for a substantial effect of spatial knowledge on navigation control (BF = 2288.885), showing that the player familiar with the destination spent more time in control (see also Figure 5). Note that we did not explicitly tell participants the other player knows the area they do not; so this effect suggests an implicit understanding that if they do not know the location, the other person might do.

We then examined whether the proportion in control measure was moderated by individual participants' characteristics (RQ2): *spatial ability* (sense of direction), and *motivation to lead* (3 subscales: *social-normative*, *non-calculative*, and *affective identity*). Figure 3 shows a trend line overlayed on a scatterplot for each parameter; note this figure includes repeated measurements per participant. The results of linear mixed-effects regression (see formula in Appendix) reveal that in line with the previous analysis, *familiarity* with the Goal area had a significant, negative effect on proportion in control ($b = -0.240, SE = 0.064, p < 0.05$). While a positive trend can be observed for *affective identity* and *non-calculative* (motivation to lead sub-scales) the effect was not significant; however we observed a trend for an interaction of *social-normative* and familiarity ($b = -0.074, SE = 0.039, p = 0.066$).

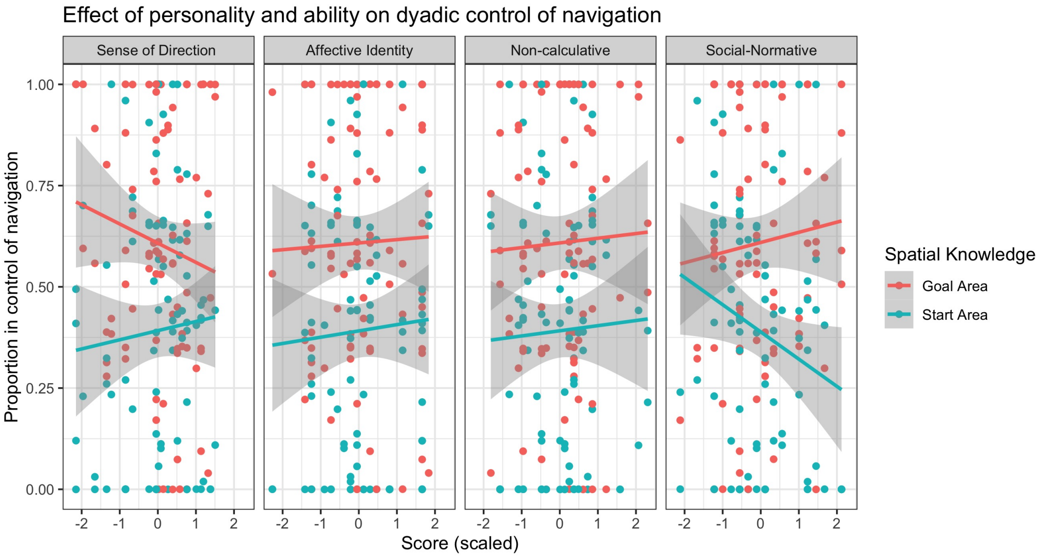

Figure 3 Scatter-plot showing the relationships between each players' characteristics and proportion in control of the navigation in each trial.

Finally, we also explored participants' responses to the post-experiment survey with regards to strategies for collaborative navigation (RQ3) (appendix: Figure 6 bottom). While responses vary, these are inline with the behavioural observation that participants took over control when navigating to a destination they were familiar with (64.5%), and that they yielded/exchanged control when they felt disoriented (78.8%). We can also note that 37.5% of participants report *not* strictly navigating in the area they learned.

5 Discussion and conclusions

In this pilot study, we demonstrated the feasibility and operation of a novel, non-verbal, online, collaborative navigation paradigm. We explored how people navigate collaboratively in cases where spatial knowledge is distributed, rather than shared equally, among a team (here dyads). Results indicated a positive effect of spatial knowledge of the destination area, as well as interactions between spatial knowledge with spatial ability and *social normative* motivation to lead. These interactions will be further explored in future studies. Two limitations are that non-verbal and remote collaborative navigation may differ from everyday situations; also a larger sample will enable more elaborate statistical analyses. Future work could consider additional analyses of navigation trajectories, beyond shortest paths.

To summarise, here we report on the pilot of a novel, computer-based study paradigm to test non-verbal collaborative navigation under spatial information uncertainty. Our results demonstrate the effectiveness of this paradigm, and open up new opportunities for the study of collaborative navigation, such as large online experiments. Our future work includes a comprehensive experiment to understand navigation under spatial information uncertainty.

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A Appendix

A.1 Virtual environment & navigation tasks

Figure 4 The virtual town, goal locations, and navigation tasks.

The virtual town, consisting of two neighbourhoods (red or blue paving), of approximately equal number of streets and surface area. Green circles indicate goal locations (numbered). Dashed arrows indicate the starting point and the destination of each navigation task, each starting in one neighbourhood and ending on the other. Start locations were chosen to allow multiple alternatives to the goal (i.e. not along the same street). Goal locations (destinations) were chosen so that they that in each neighbourhood 3 goals were closer to the boundary with the opposite neighbourhood and 3 goals towards the edge of virtual town.

A.2 Proportion in control

Proportion in control was influenced by spatial knowledge.

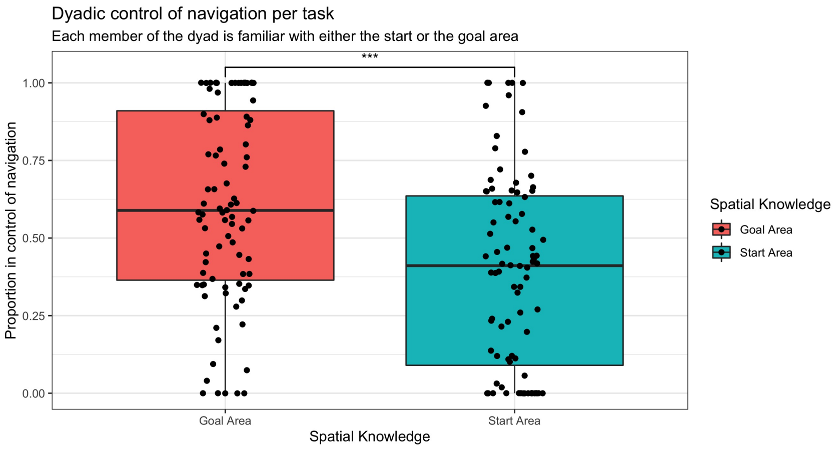

Figure 5 Boxplot showing which participant was more in control during a wayfinding trial, as a proportion of the entire trial. We can observe that overall, the player of the dyad that was familiar with the neighbourhood of the destination (goal area) assumed more navigation control.

A.3 Analysis tools

All analyses were performed in *R* (version 4.1.1), using the following R-packages: *dplyr* (version 1.0.7), *lubridate* (version 1.7.10), *sjPlot* (version 2.8.10), *purrr* (version 0.3.4), *tidyR* (version 1.1.3). Graphics were made using *ggplot2* (version 3.3.5), *sjPlot* (version 2.8.10) and *patchwork* (version 1.1.1). Statistical analyses were performed using the R-package *BayesFactor* (version 0.9.12-4.2) and *correlation* (version 0.6.1).

A.4 Linear mixed-effects model

We fitted a linear mixed effects regression model to understand the interaction between spatial knowledge and invidual's characteristics. The with formula: $proportion \sim Familiarity + sbsod.score.s : Familiarity + Affective.Identity.s + Noncalculative.s + Social.Normative.s : Familiarity + (1 + Familiarity|pair : ParticipantID) + (1|Order)$

A.5 Self-reports

After completing the experiment, participants were asked to self-report if they found the task and instructions clear, whether they perceived the visual cues distinguishing the two neighbourhoods, and their navigation control strategies (Figure 6).

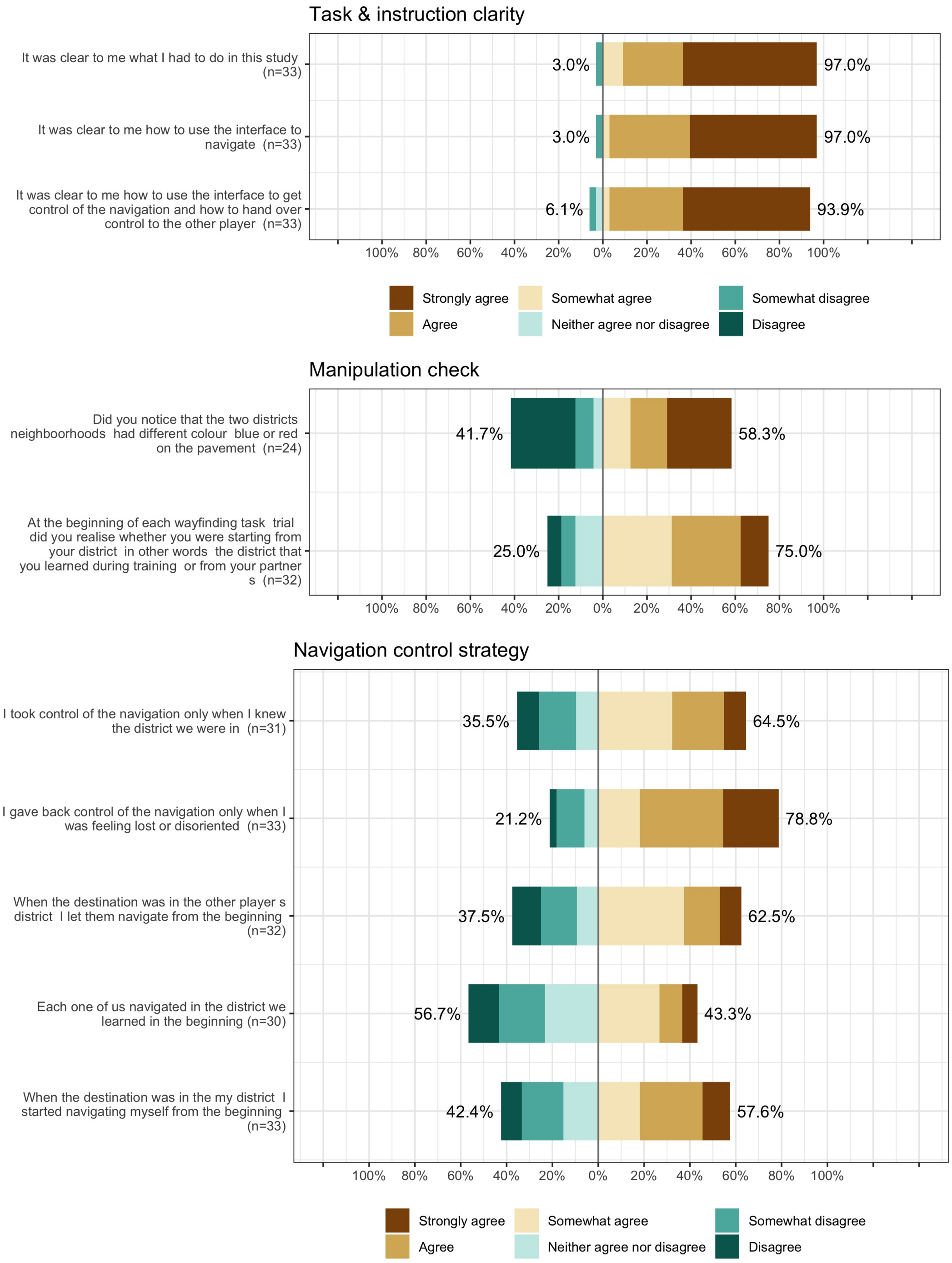

Figure 6 Top: Manipulation check; after completing the experiment, participants were asked if they understood the instructions. Bottom: Participants post-experiment self-reports reveal various strategies of collaborative navigation.