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Authors

Montello, Daniel R
Davis, Rie C
Johnson, Mike
et al.

Publication Date

2023-05-01

DOI
10.1016/j.jenvp.2023.102004

Journal of Environmental Psychology 87 (2023) 102004

Contents lists available at ScienceDirect

Journal of Environmental Psychology

journal homepage: www.elsevier.com/locate/jep

The symmetry and asymmetry of pedestrian route choice☆

Daniel R. Montello [a,*], Rie C. Davis [a], Mike Johnson [a], Elizabeth R. Chrastil [a,b,**]

[a] Department of Geography, University of California, Santa Barbara, United States
[b] Department of Neurobiology & Behavior, University of California, Irvine, United States

ARTICLE INFO

Handling editor: Chiara Meneghetti

Keywords:
Route choice symmetry
Pedestrian behaviour
Spatial analysis

ABSTRACT

During everyday activities, people sometimes take a different route in one direction than they do on the return trip. Yet we do not fully understand the degree to which people choose particular routes, and this asymmetry has yet to be systematically quantified. To address these questions, we designed a multi-segment route on a college campus that included two pairs of reciprocal segments, in which young adult participants ($n = 52$, ages 18–23, 36f/16m) walked from place A to place B and then later in the route—without being alerted to its reciprocal nature—went from place B to A. We used GPS tracking to record the routes our participants walked, and we developed novel continuous measures of route dissimilarity which we used to analyse both reciprocal and nonreciprocal routes. Our results indicate that there is substantial asymmetry in route choice but no consistent tendency for individual participants to take symmetric or asymmetric routes. We also found substantial variation across participants in the route taken across all segments, but this natural variability in routes did not entirely explain the asymmetries we observed, suggesting that there is systematic asymmetry in route choice that goes over and beyond the tendency simply to take variable routes. Overall, our controlled test of route choice balanced experimental control with ecological validity. Combined with our novel measures of route (dis)similarity, these findings provide a new perspective on this classic route choice problem.

1. Introduction

Whether traveling to and from work or the grocery store, people sometimes take a different route in one direction than they do in the other. Yet it is not fully understood to what degree people vary their routes as they move from place to place, and this holds for routes in reciprocal directions between pairs of places. This issue has implications for basic theories of human spatial cognition and behaviour, as well as for applied questions of transportation and urban planning. Myriad factors likely influence route choice, including the traveller's knowledge and personality, constraints on travel such as time and fuel, the purpose of travel, the traveller's transportation mode and resources, the distance being travelled, and the structural options for different routes available in the environment. In most cases, travellers have several route options for their particular destination(s), especially in situations where travel occurs in open fields, plazas, and the like, where travellers are not restricted in their route choice to a predetermined and fixed set of path[1] structures, such as roads, trails, or hallways. The question of how much travellers vary their route choices is central to behavioural scientists, planners, and engineers in various disciplines (Bovy, 2009; Meilinger, Frankenstein, & Bülthoff, 2014; Prato, 2009; Skov-Petersen, Barkow, Lundhede, & Jacobsen, 2018). Route choice is a computationally challenging problem, but understanding more about how humans try to optimize their trajectories is important for the development of navigational aid systems as well as for transportation and signage systems. In the research presented here, we describe an experimental study of route

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☆ Preliminary results of this research were presented at the 60th Annual Meeting of the Psychonomic Society, Montréal, Québec, Canada. We thank members of the Route-Choice Lab group for their help with material preparation, data collection and processing, and discussions of ideas and studies: Julianne Amores, Michaela Borrelli, Anthony Cowell, Sheridan Lanz, Jessica Luo, Grace Nicora, Josette Morgan, Reasha Sharma, Thomas Smith, Olga Tambazidis, and Thomas Watson. We thank Kostas Goulias, Ed Manley, Kai-Florian Richter, and Sabine Timpf for advice on literature, and we thank the editor and three anonymous reviewers for comments on an earlier version of this manuscript. ERC was supported in part by the National Science Foundation BCS-1848903.

* Corresponding author.

** Corresponding author. Department of Neurobiology and Behavior, University of California, Irvine, CA, 92697, United States.

E-mail addresses: montello@geog.ucsb.edu (D.R. Montello), chrastil@uci.edu (E.R. Chrastil).

[1] We use the term "path" to refer to a linear physical structure in the environment along which travel occurs (typically by design, e.g., a street or footpath) and "route" to refer to a linear pattern of locomotion (Montello, 2005).

https://doi.org/10.1016/j.jenvp.2023.102004
Received 6 March 2022; Received in revised form 21 February 2023; Accepted 28 March 2023

choice by pedestrians on a college campus, focusing specifically on the symmetry of choices by individuals walking at different times in reciprocal directions between pairs of places.

1.1. Symmetry of route choices: the similarity of reciprocal routes

An intriguing question about route choice is to what degree travellers who have made a trip from place A to place B choose the same route in returning from B to A—to what degree do they display *symmetry* or *asymmetry* in their route choices when going reciprocally 'to' and 'fro' between two places? The answer to this question can help reveal how people make route choices in general, how much variability or consistency they exercise in their route choices, the properties they try to optimize when they choose routes, how well they carry out this optimization, and whether people apply particular heuristics consistently in their route choices over time. For example, finding asymmetry in route choice could indicate that the mental representation of the route from A to B differs from that of B to A. Such a finding would require a greater understanding of the cognitive mechanisms involved in creating asymmetric mental maps. Determining the degree of asymmetry and the source of these asymmetries—whether cognitive, heuristic, or related to the structure of the environment (or all three)—could help simplify models of route choice behaviour more broadly.

Although the study of the symmetry of route choice has rich potential to illuminate issues of route choice, there is relatively little research on it. Overall, previous studies find that both symmetric and asymmetric choices are common, although travel modality is important in this regard. The decision processes people use to choose routes and the values of route properties can differ substantially across common modes of terrestrial travel such as walking, biking, driving, and using public transit. Stern and Leiser (1988), for instance, found that professional drivers, such as taxi drivers, were more likely to pick symmetric routes than were amateur drivers, who were quite likely to choose asymmetric routes. The researchers proposed that symmetric choices necessarily reflected better survey knowledge of the city, which would likely be better developed among professional drivers. Their data did not compare reciprocal route choices within-subject, but aggregated and compared between groups.

In a multi-study paper that was not focused on route choice but on choices in general contexts, Christenfeld (1995) did find substantial asymmetric route choices in two of their studies conducted either with a schematic map of a small city or by observing pedestrians on a college campus. Their participants preferred to pick the final of three route alternatives no matter whether they were traveling from A to B or from B to A. They suggested this revealed a route-choice preference for taking the final option, carried out in order to minimize mental effort. Like the Stern and Leiser (1988) study, however, Christenfeld also used a between-subjects research design, comparing route choice in reciprocal directions by aggregating over groups rather than comparing individual choices in both directions.

Golledge (1995) conducted two exploratory studies in which he observed students who were asked either to choose routes from a map or to walk short lengths between places on a college campus. Both studies revealed asymmetric route choice on as many as half or more of the trials. However, the campus study involved choices among very short and similar routes that took less than 2 min to walk and simply wound to one side or the other of several large planter boxes, with the entire route environment visible throughout. This study did compare reciprocal choices within individual research participants.

In two studies, Bailenson, Shum, and Uttal (1998) had research participants choose routes from fictitious map-like images or schematized campus maps; in both studies, the entire set of all alternative routes was simultaneously visible on the images. They reported a sizable proportion of asymmetric reciprocal route choices between A and B. The researchers hypothesized that asymmetric choice was systematically due to participants specifically preferring to first choose long, straight segments over curved, turn-filled segments, even though the total length of the resulting routes in both directions was equal, or even if the preferred choice was longer than an alternative. They noted that this heuristic would readily account for the findings of Christenfeld (1995). Once again, the researchers employed a between-subjects research design, comparing choices in the two reciprocal directions made by different groups of participants. As a follow-up, Bailenson, Shum, and Uttal (2000) reported five studies of route-choice symmetry, four based on map-like images and the fifth based on several schematized maps from actual US college campuses. Again, they found substantial asymmetric route choices, with participants preferring alternatives that started with longer straight segments before displaying curves and turns, dubbing it the “initial segment strategy”. Again, their comparisons were between-subjects. Notably, participants in the studies by Bailenson and his colleagues experienced the environments and chose routes via maps from a top-down perspective rather than directly in an actual environment, and they never actually walked on the chosen routes.

An extensive and controlled study on pedestrian route choice was reported in a dissertation by Pingel (2010). Carried out on a university campus, he had participants walk multi-segment routes in a within-subjects design that included reciprocal as well as nonreciprocal segments. He compared walked routes in terms of their length relative to the minimum length between particular nodes. Pingel explicitly considered various choice strategies to explain the routes he observed; he also assessed individual-difference variables, including the cognitive factors of survey reasoning ability and sense-of-direction, and the personality factors of risk taking and strategic thinking. Pingel made the important point that some asymmetric choice on reciprocal routes would occur just as a reflection of normal variation in route choice on any routes; a person does not always choose the same route from node A to node B, so they would not be expected always to choose the same route when they go back to A. In fact, he found consistent asymmetry for some of his reciprocal route segments over and above general variation in route choice. Although Pingel's work provides some important insights into the symmetry of route choice, his assessment of the similarity among routes, whether reciprocal or otherwise, was essentially qualitative. In the current work, we develop and evaluate quantitative indices of route similarity both for reciprocal and nonreciprocal routes.

A recent study by Malleson et al. (2018) analysed smartphone-recorded tracks for a very large sample of pedestrians (over 6000) in the greater Boston area, over a year's time. Participant tracks were processed by an algorithm that matched walkers' routes to streets in this extensive urban network. These researchers also examined the symmetry of route choices, but aggregated over individual walkers. They found nearly 15% of the trips were asymmetric in the aggregate, meaning that about 85% of the trips between two locations followed the same routes in either direction. Interestingly, the researchers did not find a relationship between tendencies toward symmetry and the absolute lengths of routes (i.e., the trip length), but they did find increased asymmetric route choices when alternative routes were all close to being optimally short in length. A more recent study from the same group also found asymmetries in about 20–30% of trips, aggregated over different navigators. They found that taking the route most directly pointing to the destination, which they term vector navigation, was the most likely factor in these route choices (Bongiorno et al., 2021).

1.2. The present experiment

Overall, we see that some work has been conducted on the symmetry of route choice, but the approaches of these studies leave some issues unclear. Since travel modality undoubtedly influences the prevalence of symmetric route choices, research on drivers or transit users, for instance, does not easily generalize to route choice by pedestrians. Most studies have used between-subjects designs, which do not conclusively show whether the same individual makes symmetric choices when traveling on reciprocal routes. And several studies used overhead map-like displays and hypothetical scenarios, rather than first-person experiences of travellers actually locomoting in real environments. Finally, existing studies have essentially scored reciprocal route choices dichotomously as being the "same" or "different," almost always a partially arbitrary judgment, especially in cases of pedestrian travel. Pingel (2010) did compare the lengths of the 'to' and 'fro' routes for a reciprocal pair, but he did not otherwise quantify the degree of their dissimilarity; two pairs of routes of nearly the same distance might otherwise be quite similar or dissimilar. Both dichotomous scoring and comparisons of length leave unexamined the dissimilarity of routes, defined as the degree to which they deviate in location from perfect overlap, whether of reciprocal or nonreciprocal routes (Ranacher & Tzavella, 2014, review measures for comparing movement trajectories that incorporate temporal as well as spatial similarity).

In the present experiment, we developed novel continuous measures of route dissimilarity which we used to analyse both the reciprocal routes (within-subject) and, for comparison, the nonreciprocal routes (between-subject). We observed travellers' actual route choices on a college campus, a revealed-preference approach to collecting data on people's choices of routes (Abdel-Aty, Kitamura, & Jovanisa, 1997; Malleson et al., 2018). We recorded choices by GPS-tracking the routes our participants actually walked between several places on the campus. The GPS-tracking approach allowed for our participant to be relatively unconstrained by path structure in their route choice—a participant could have cut across a grassy area and we simply followed that trajectory. Our study had people choose routes in a real environment that they actually walked, potentially making it more readily comparable to day-to-day navigation than studies that use maps, virtual environments, or hypothetical scenarios. At the same time, we manipulated which places people travelled between in a controlled experimental design. Our participants mostly knew the experimental setting well, although they probably had not travelled directly between all the places we asked them to journey over, thus requiring them to integrate their knowledge of campus and likely create novel routes never taken before.

Our major focus in this experiment was on choice symmetry—to what degree did people take the same route from B to A as they previously did from A to B? First, we addressed the extent of asymmetry on reciprocal segments. To do this, we asked our participants to walk a multi-segment route between several places on campus in a set order that was the same for each participant. Nested within the sequence of segments were two sets of reciprocal segments wherein participants walked from place A to place B ('to') and then later in the walk, walked from place B to A ('fro'). By embedding these segments without pointing out their reciprocal nature to subjects, we were able to distract participants from our interest in the symmetry of their reciprocal choices. This design provided two pairs of reciprocal segments to explore choice symmetry, which not only gave us some ability to explore the generality of our findings but afforded us the ability to compare our participants' tendencies to choose symmetrically on the two pairs, addressing the novel question of whether such a tendency is consistent within individuals—that is, whether people display a consistent trait to be symmetric or asymmetric route reversers. Therefore, we computed a novel measure of asymmetry called the *Asymmetry Index*. We compared asymmetry for the two pairs, which differed in length, and tested whether there were gender differences or interactions in asymmetries.

Next, we addressed the extent to which asymmetry can be explained by random variation on non-reciprocal segments. We nested our reciprocal segments within a larger set of nonreciprocal route segments in our within-subjects design. By doing so, we provided a baseline measure of general between-subject variance (dissimilarity) in choice on nonreciprocal routes, which we computed as the *Dissimilarity Index*. We then compared this baseline to the within-subject variance in choice on reciprocal routes by computing dissimilarity in each direction (A to B and B to A) with the *Reciprocal Dissimilarity Index*. Substantial systematic asymmetry of route choice, over and above simple variation, would lead to a Reciprocal Dissimilarity Index that is greater than the regular Dissimilarity Index. Based on previous literature, we expected substantial asymmetry of route choice, which our technique now allowed us to quantify. The question of whether this asymmetry would be over and above simple variation has not been addressed in previous literature, but we thought it was likely that asymmetry would play a particularly strong role in route choice, and therefore expected this result.

2. Method

2.1. Participants

Participants were students at the University of California, Santa Barbara (UCSB), enrolled in an introductory human geography course and participating for a small amount of course credit; however, the great majority were not geography majors. A total of 58 participants were tested, but only 52 provided complete and valid data because of technical problems with the tracking watch. Of these 52, 36 were females and 16 males; their mean age was 19.2 years (18–23 years). We used previous work (e.g., Bailenson et al., 1998, 2000; Brunyé et al., 2010) as guides for our sample size, which used around 24 participants for within-subjects contrasts. Conducting a post-hoc power analysis on our final sample size of 52, we have achieved 94.3% power to detect a medium size (0.5) effect, and 56.5% power to detect a smaller (0.3) effect.

Participants were most likely quite familiar with the campus layout, having attended this university for a mean of 13.4 months (2–42 months), although we did not directly ask them their familiarity with the campus or the route segments. Data were collected over four separate academic terms, a 9-month period from November 2018 to July 2019. All participants gave their informed consent to participate in accordance with the UCSB IRB. The IRB approved all procedures for this study.

2.2. Design

Section A of the Supplemental Material contains a glossary of the terms we use throughout the methods and analysis for reference. Each participant walked the same 8-segment test route starting and ending at the same place (Fig. 1); Section B of the Supplemental Material provides details concerning the design of the route. Participants travelled between the four nodes in the sequence indicated on the right of Fig. 1, resulting in an overall route consisting of eight segments. Two pairs of route segments were reciprocal—they were segments walked in both directions at some point during the experiment. The first pair (Pair A) was created by having participants walk from Ellison Hall to the Bus Loop as the first segment (Segment 1) and from the Bus Loop to Ellison Hall as the fifth (Segment 5); the second pair (Pair B) was created by having participants walk from the Bookstore to Physical Sciences North as the third segment (Segment 3) and from Physical Sciences North to the Bookstore as the seventh (Segment 7). Henceforth, we refer to Segments 1 and 5 as 'A-to' and 'A-fro,' respectively, and Segments 3 and 7 as 'B-to' and 'B-fro,' respectively. The two segments making up each reciprocal pair were thus contained within a series of other segments in an obscure pattern to provide nonreciprocal comparison segments without signalling our interest in route-choice symmetry. The order of the segments (and reciprocal pairs) were chosen within the constraints of starting and ending the entire path at Ellison Hall and not repeating the reciprocal segments back-to-back.

2.3. Materials

We recorded the walked tracks of participants with GPS-enabled tracking watches (Garmin Forerunner® 25). Section C of the Supplemental Material provides details concerning the data recorded by the watch and its processing.

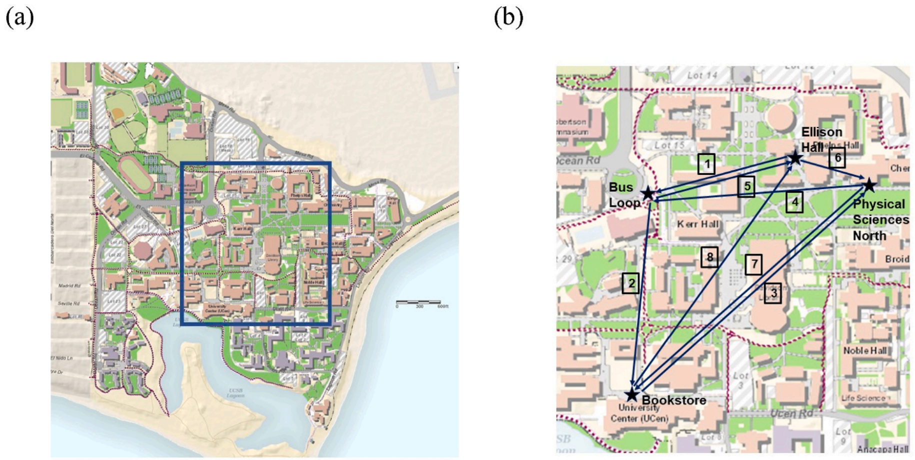

Fig. 1. *Note*: Map of the UCSB campus (a), with the area containing our test route shown in the inset box. Inset box enlarged (b) shows the four nodes used to anchor the segments of our test route. The vectors indicate the order that participants walked between the nodes (not the exact track they walked), starting at Ellison Hall with Segment 1 and ending at Ellison Hall with Segment 8. Segments 1 and 5 are the reciprocal routes between Ellison Hall and the Bus Loop (A-to and A-fro); Segments 3 and 7 are the reciprocal routes between the Bookstore and Physical Sciences North (B-to and B-fro) (source: UCSB Department of Geography).

Fig. 1. Map of the UCSB campus and the test route segments.

2.4. *Procedure*

We tested participants individually. They came to our lab in Ellison Hall, signing an informed consent form describing the study and their ethical rights. Participants were told they would be taking part in a study to “understand how participants travel on a day-to-day basis around the UCSB campus.” We explained that the watch would track their location at all times with GPS; we then placed it on their wrist. Then the campus map with the node locations marked was briefly shown to participants, who were told these were the locations they would visit. Participants were also briefly shown photographs of each location at this point, to make sure all participants would be clear about the identities and locations of the nodes. In addition, we wanted to reduce ambiguity about the specific locations (e.g., the kiosk at the bus loop) so that the route endpoints were very nearly the same across participants. Neither the map nor the photos were shown again. We walked participants outside to the starting node, explaining that we would give them the name of another location on campus and have them walk to it. Then we would give them the name of another location to which they would walk, and so on. The experimenter walked a few feet behind at all times. We then had them walk the first segment. After the final segment was completed (at the same node where they had started), the watch was retrieved and participants were recorded for credit. The entire procedure required about 50 min per participant to complete.

2.5. *Analysis of route tracks*

2.5.1. *Asymmetry Index*

Considerable processing was required to prepare the walked tracks stamped in the GPX files for analysis (details are provided in Section D of the Supplemental Material). Our major interest was in the symmetry of the routes that participants walked in the two directions between the nodes of each of our two pairs of reciprocal segments. As explained above, we wished to continuously quantify the degree of locational symmetry/asymmetry between the segment tracks participants walked reciprocally between nodes, going beyond merely classifying them as “same” or “different.” Thus, we created a measure of the (a)symmetry between two reciprocal segment tracks we refer to as an *Asymmetry Index*. To do this, we first measured the area between the two walked tracks in each reciprocal direction (Fig. S1). We ignored the direction of travel and the ordinal positions of each segment (e.g., ignoring whether the ‘to’ segment was north or south of the ‘fro’ segment); we also ignored whether the two tracks crossed each other once or more. Calculated in this way, walked tracks that were very symmetric in each direction had a very small area between them, while tracks that were very asymmetric—very different in the two directions—had a large area between them. We then standardized this calculation by dividing by the area of the bounding rectangle that has the two segment endpoints at its opposite corners. Thus, our calculation of asymmetry results in an index that essentially expresses the proportion of this rectangle that is taken up by the nonoverlapping area of the two segment tracks. This ratio is multiplied by 100% to get a measure interpretable as a percentage, with a minimum of 0% and a practical maximum of 100% (Fig. S2). Details of our calculation of the Asymmetry Index are provided in Section E of the Supplemental Material.

2.5.2. *Dissimilarity Index*

We also collected tracks for the other segments of our route, segments that participants only walked in one direction (the same direction by all participants). As we mentioned above, route-choice disagreement among different participants provided a baseline of route-choice variability to help us evaluate the degree of asymmetry among reciprocal route segments. We created a measure of the dissimilarity among the tracks from all the participants on each route segment, including nonreciprocal segments, that we refer to as a *Dissimilarity Index*. We designed it as analogously as possible to the Asymmetry Index we calculated just for reciprocal segments. The Dissimilarity Index first quantifies disagreement among the tracks of different participants going in the same direction between a given pair of nodes by assessing the nonoverlapping area of each participant’s track with each of the other participants’ tracks, compared pairwise (Fig. S3). We then standardized across pairs in the same way as the Asymmetry Index. As with the Asymmetry Index, very similar tracks (in this case, from two different participants) had a very small area between them (minimum of 0%), while very different tracks had a large area between them (practical maximum of 100%). Details of our calculation of the Dissimilarity Index are provided in Section F of the Supplemental Material.

2.5.3. *Reciprocal Dissimilarity Index*

Finally, we explored the extent to which the route asymmetry we found could simply be an expression of the baseline variation in route choice that we examined with the Dissimilarity Index. Just as different people generally do not choose the same route track between a given pair of nodes in a given direction, an individual person may not choose the same route track going in each direction between a reciprocal pair of nodes. This difference could be just that they normally tend to vary their route choices, especially when alternative routes exist which do not greatly differ in properties travellers are trying to optimize. In other words, did the magnitude of route asymmetry within individuals differ from the magnitude of route dissimilarity across individuals on those same route segments?

There are several analytic approaches one might take to addressing this question. We took the approach of comparing the average dissimilarity of the track a participant walked in one direction of a reciprocal pair of segments to the tracks all other participants walked in the other, reciprocal direction. To do this, we modified our calculation of the Dissimilarity Index for the two pairs of reciprocal segments. That is, we calculated the difference in non-overlapping area between each person and all the others as in the Dissimilarity Index, but for the target person we used the 'to' direction with all others' 'fro' direction (and we computed the opposite as well). We termed this measure the *Reciprocal Dissimilarity Index* (Fig. S4), with a minimum of 0% and practical maximum of 100%. Details of our calculation of the Reciprocal Dissimilarity Index are provided in Section G of the Supplemental Material, along with discussion of alternative analytic approaches to addressing this question.

If route-choice in the two directions of a reciprocal pair of segments were perfectly symmetric, then the Dissimilarity Index should be exactly the same regardless of the direction of travel. Thus, it should not matter whether it is based on pairwise comparisons of a participant's track in one direction with the tracks of each of the other participants in the *same* direction (regular Dissimilarity) or on a participant's track in one direction with the tracks of each of the other participants in the *opposite* direction (Reciprocal Dissimilarity). In contrast, if participants' choices in the two directions are *systematically* asymmetric—over and above baseline variation in route choice—then the direction should matter. The dissimilarity of their tracks with other participants should be greater when based on others' tracks in the opposite direction than when based on others' tracks in the same direction. That is, systematic asymmetry would add extra variation to reciprocal choices over and above choice variation in a single direction. Substantial systematic asymmetry of route choice, over and above simple variation, would lead to a Reciprocal Dissimilarity Index that is greater than the regular Dissimilarity Index. In contrast, asymmetry no greater than the normal variability in route choice would lead to Reciprocal Dissimilarity that is about equal to regular Dissimilarity.[2]

2.5.4. Additional variables

Throughout our analyses, we included sex because a number of studies have shown sex differences in navigation ability and survey knowledge use (Gagnon et al., 2018; Nazareth, Huang, Voyer, & Newcombe, 2019), differences which could play a role in route choice. Further, females could also have more safety concerns when navigating, and given that women have higher spatial anxiety (Lawton, 1994; Schmitz, 1999), these factors could also differentially affect route choice. In addition, we examined Pearson correlations of the number of months participants had spent on campus with our various outcome measures.

3. Results

3.1. Reciprocal asymmetry

Tracks from all participants for all eight segments are shown in Fig. 2, the two pairs of reciprocal segments (Segments 1 and 5 of Pair A, and 3 and 7 of Pair B) on the left and the four nonreciprocal segments (Segments 2, 4, 6, and 8) on the right. We first examined the asymmetry of route choice for the reciprocal Pairs A and B by calculating the Asymmetry Index we described above for each participant. Fig. 3 shows example pairs of reciprocal tracks and their intervening areas for four participants, along with the values of their Asymmetry Indices. Some participants took very symmetric routes and others took quite asymmetric routes, but not necessarily equivalently between each pair of reciprocal segments. Over all participants, the mean Asymmetry Index for Segment Pair A was 16.6% (SD = 10.4), with a range of 1.9–38.6%; the mean for Segment Pair B was 14.6% (SD = 13.2), with a range of 1.1–56.2% (Table 1).

To test whether these Asymmetry Indices significantly exceeded perfect symmetry, we calculated one-sample t-scores of their difference from the minimal value. As we noted in Section E of the Supplemental Material, although the theoretical minimum would be 0% when tracks are perfectly symmetric, this would be very unlikely in practice even with near-perfect symmetry. Instead, we compared the Asymmetry Indices for Pairs A and B to the smallest value we observed in our data, 1.9% for Pair A and 1.1% for Pair B. Both indices significantly exceeded these minima: $t(51) = 10.18$, $p < .0001$ for Pair A, and $t(51) = 7.37$, $p < .0001$ for Pair B.

We also compared the indices for the two pairs to each other in a mixed 2-way ANOVA with segment pair and participant sex as within- and between-subject variables, respectively. The very similar mean values of the two pairs did not significantly differ ($F[1, 50] = 0.57$, $p = .45$), suggesting that participants' tendency to choose symmetric routes did not vary much with segment length (the length of the Euclidean Connector, which we used to standardize the two routes for their size, is 276 m for Pair A, 562 m for Pair B). At the same time, the Asymmetry Index hardly differed between female and male participants, either for Pair A ($M_F = 16.0\%$, $M_M = 18.0\%$) or Pair B ($M_F = 14.1\%$, $M_M = 15.8\%$). These means did not differ as a main effect of sex ($F[1, 50] = 0.60$, $p = .44$) nor as an interaction of Pair and sex, ($F[1, 50] = 0.00$, $p = .96$). We also found that the Asymmetry Index did not relate to the number of months participants had been on campus ($r_{Atf}[51] = -0.07$, $p = .62$; $r_{Btf}[51] = -0.19$, $p = .18$); because of the restricted values of our participants' months on campus (discussed in Section H of the Supplemental Material) and the lack of correlations with Asymmetry, we did not include it as a covariate in any further analyses. Finally, and perhaps most notably, the Asymmetry Indices for the two pairs of segments were not significantly correlated across participants, and to the degree they were, it was negative, $r[52] = -0.15$, $p = .39$. This suggests that there was no particular tendency for people always to use the same route or always to take different routes.

As an alternative way to address the asymmetry of the tracks walked for the pairs of reciprocal route segments, we looked at the lengths of the tracks participants walked on the 'to' and 'fro' segments, relative to each other (as did Pingel, 2010) (presented in detail in Section I of the Supplemental Material). These walked lengths were substantially longer for Segment A-to (334.7 m) than for its reciprocal Segment A-fro (313.9 m), $t(51) = 5.45$, $p < .0001$. But the mean walked lengths were quite similar for Segment B-to (697.3 m) and its reciprocal Segment B-fro (689.9 m), and did not significantly differ, $t(51) = 0.83$, $p = .21$. This may at first seem paradoxical—the Asymmetry Indices for the two pairs of segments did not significantly differ from each other, suggesting that the shapes of the reciprocal alternatives for both pairs were about equally far apart from each other (as in the tracks by Participant 54 in Fig. 3). Nonetheless, as we just reported, the alternatives taken across participants for Pair A differed relatively more in length from each other on average (difference of 20.8 m) than did those for Pair B (difference of 7.4 m). The explanation is that participants as a group more consistently chose the same alternatives in each direction for Pair A, while they less consistently chose alternatives for Pair B (as indicated by the analyses of dissimilarity in Section H of the Supplemental Material). That is, participants were collectively more likely on Pair A to choose the same particular route as each other on A-to and then choose the same particular different alternative on A-fro; in contrast, they were less consistent in choosing particular alternatives on Segments B-to and B-fro and were thus more variable.

3.2. Dissimilarity across participants

We also computed a novel Dissimilarity Index as a between-subjects index reflecting the extent to which participants chose routes on a given segment dissimilar to those chosen by other participants on that segment. As we expected, dissimilarity was greater on some segments

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[2] We can think of no reason that Reciprocal Dissimilarity would ever be reliably less than regular Dissimilarity.

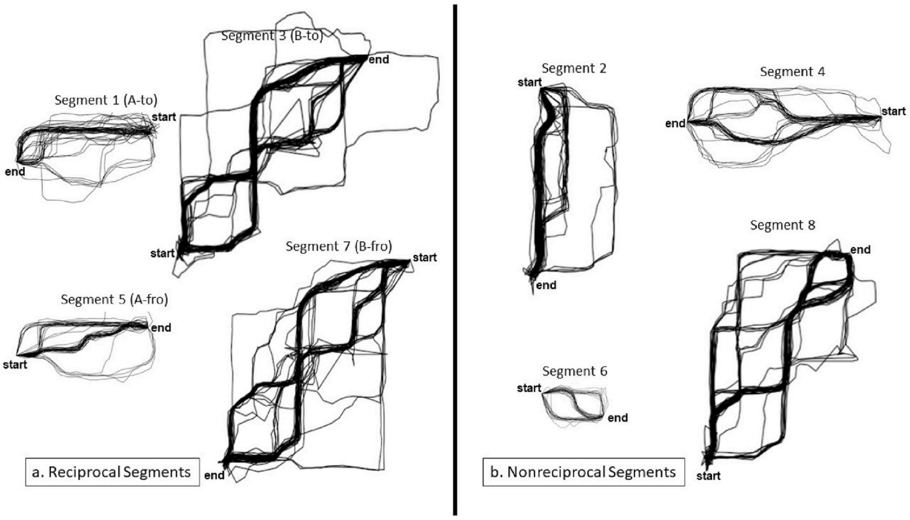

Fig. 2. Tracks from all 52 participants for reciprocal and nonreciprocal segments.

Participant 54: $AI_{15} = 38.6$ $AI_{37} = 31.2$

Participant 53: $AI_{15} = 1.9$ $AI_{37} = 55.6$

Participant 5: $AI_{15} = 9.2$ $AI_{37} = 14.4$

Participant 9: $AI_{15} = 28.0$ $AI_{37} = 1.7$

Fig. 3. Sample reciprocal segment tracks from four participants and their Asymmetry Index (AI) values for Pair A (denoted AI_{15}) and Pair B (denoted AI_{37}). The bounding rectangles are based on their respective Euclidean Connectors as diagonals; track measures are standardized by dividing by the area of these rectangles (see Equation 1 in Section E of the Supplemental Material).

Table 1

Frequency distribution of Asymmetry Index values for reciprocal segment Pairs A and B (N = 52). Pair A is composed of segments 1 and 5, and Pair B is composed of segments 3 and 7.

%	Pair A	Pair B
0.0–4.9	9	16
5.0–9.9	9	6
10.0–14.9	9	13
15.0–19.9	5	3
20.0–24.9	6	4
25.0–29.9	9	5
30.0–34.9	3	2
35.0–39.9	2	0
>39.9	0	3

than others. As shown in Section H of the Supplement, participants were most variable in their route choices on Segment 6, the shortest segment. In fact, the correlation of mean dissimilarity with the length of the Euclidean Connector across the eight segments equalled −0.64, indicating that route choices tended to be more variable for shorter route segments. In contrast, there was only a very weak tendency for dissimilarity to increase for later segments, with mean dissimilarity correlating only 0.29 with segment order. Dissimilarity also did not differ between female and male participants overall or in its specific pattern across segments, nor did dissimilarity vary as a function of months participants had been on campus.

Likewise, the standardized lengths of the walked tracks on each segment differed across segments. As presented in Section I of the Supplement, participants chose the relatively longest routes on Segment 1 and then Segment 2. In fact, the correlation of mean standardized walked length with segment order across the eight segments equalled a robust −0.82, indicating that participants chose more efficient routes as the experiment went on. This probably reflects increasing fatigue (mental or physical) as the experiment proceeded. In contrast, there was only a very weak tendency for relative walked length to be longer for shorter segments, with mean walked length correlating only −0.32 with the length of the Euclidean Connector. Relative walked length also did not differ across genders or as a function of months on campus.

3.3. Does dissimilarity explain asymmetry?

As discussed above, we calculated dissimilarity in order to explore the extent to which the route asymmetry we found could simply be an expression of the baseline variation in route choice. We addressed this by comparing the regular Dissimilarity Index to the Reciprocal Dissimilarity Index. Substantial systematic asymmetry of route choice, over and above simple variation, should lead to a Reciprocal Dissimilarity Index that is greater than the regular Dissimilarity Index. In contrast, asymmetry no greater than the normal variability in route choice would lead to Reciprocal Dissimilarity that is about equal to regular Dissimilarity. In fact, we found that for the reciprocal segments of Pair A, the Reciprocal Dissimilarity Index was 23.4%, which is greater than the average regular Dissimilarity Index of the pair members (Segments 1 and 5)—20.0%. A paired *t*-test revealed that the difference between these two types of Dissimilarity indices was significant, $t(51) = 6.59$, $p < .0001$. This indicated that the between-segment variability on this pair, calculated reciprocally between segments, was greater than the within-segment variability calculated in a single direction alone—evidence for systematic asymmetry in route choice. For Pair B, the indices did not differ as much for the two segments. The Reciprocal Dissimilarity Index for Pair B was 18.3%, just a little larger than the regular Dissimilarity Index of 18.0%. Nonetheless, this small difference was nearly significant at the 0.05 level, $t(51) = 1.93$, $p = .059$. Therefore, the between-segment variability on Pair B, calculated reciprocally between segments, was again, at least marginally, greater than the within-segment variability calculated in a single direction alone.

4. Discussion

We examined the degree of symmetry of the route choices made by pedestrians in a controlled experiment conducted in the naturalistic setting of a university campus. Compared to many other studies on route-choice symmetry, we used a within-subject design which allows us to directly compare a person's choice of routes walking in one direction ('to') between places to their choice walking in the opposite direction ('fro')—exactly reciprocal route endpoints. Further, because we conducted a controlled experiment, we were able to compare different participants making choices between exactly the same endpoints, all of whom were making their choices within more or less the same motivational context. At the same time, our experiment took place in a real environment and involved choices revealed through actual walking, rather than hypothetical choices expressed on map-like simulations by drawing or marking options. Since we embedded our reciprocal choices within a larger set of nonreciprocal route choices, we avoided alerting our participants to our interest in the issue of choice symmetry but also generated a baseline measure of between-subject dissimilarity in choice on nonreciprocal routes to compare to the within-subject variance in choice on reciprocal routes. Finally, to quantify the (a)symmetry of route choices, we developed novel metrics that compute the locational similarities of routes as continuous ratio-level variables. These metrics go considerably beyond partially arbitrary and coarse dichotomous assessments of whether two routes are the "same" or "different." They also significantly improve on continuous comparisons based only on route length, as such comparisons treat routes as equivalent that are of the same length but possibly in very different locations. Our measures constitute novel assessments of what Ranacher and Tzavella (2014) classify as measures of spatial similarity, in contrast to measures of either temporal or spatiotemporal similarity.

In sum, our results reveal considerable asymmetry in route choice on the two pairs of reciprocal route segments we embedded in our study design. These findings broadly agree with those of previous research that found some degree of asymmetry (e.g., Bongiorno et al., 2021; Malleson et al., 2018; Pingel et al., 2010). Given the large variation observed in the Dissimilarity Index, it is unlikely that a single common heuristic (e.g., Bailenson et al., 1998, 2000) was driving this effect. As we just pointed out, we do not make a dichotomous conclusion as to how many participants chose symmetric routes and how many did not. But given the way we calculated our indices, the values can be interpreted as the percentage of the bounding rectangle with the end nodes at opposite vertices that is covered by the nonoverlap of the polygons formed by the 'to' and 'fro' segment tracks with the appropriate Euclidean Connectors. Thus, an index near 0% indicates very similar tracks, while an Index near 100% indicates tracks about as asymmetric as we expect participants could choose on our campus, assuming oriented participants. The mean value of the Asymmetry Index was nearly 17% on reciprocal Pair A and just over 14% on reciprocal Pair B, both of which significantly exceeded an estimate of actual perfect symmetry in our study based on taking the lowest value of the Index any participant earned. The values for A and B did not significantly differ from each other. Although these values may seem low compared to the maximum, even 14% is quite a substantial amount of asymmetry. For example, in Fig. 3, participant 5 has an AI of 14.4 for Pair B. This nearly average amount of asymmetry would most likely be categorized as "not symmetric" under a more qualitative classification system.

But our participants varied considerably from one another in their tendencies to walk symmetric or asymmetric routes. On reciprocal Pair A, the polygons formed by the most symmetric tracks of any participant differed by a mere 2%; that is a nonoverlap of only 760 m^2 out of a bounding rectangle formed by nodes 1 and 5 of over 38,000 m^2. To pick a somewhat arbitrary value of 5% as a measure of high symmetry (Table 1), about 17% of the participants on Pair A reached that level of high symmetry. Similarly, on reciprocal Pair B, the polygons formed by the most symmetric tracks of any participant differed by just over 1%; that is a nonoverlap of only 1800 m^2 out of a bounding rectangle formed by nodes 3 and 7 of over 158,000 m^2. About 31% of the participants on Pair B were at least as symmetric as 5%. In contrast, at the other end of the symmetry range, the least symmetric tracks of any participant on Pair A differed by a substantial 39% of the bounding rectangle; that is a nonoverlap of 14,750 m^2 out of over 38,000 m^2. Nearly 27% of the participants on Pair A had high asymmetry values of greater than 25%. On Pair B, the most asymmetric tracks of any participant differed by a very substantial 56% of the bounding rectangle; that is a nonoverlap of 88,700 m^2 out of over 158,000 m^2. Just over 19% of the participants on Pair B were more asymmetric than 25%.

Clearly, most participants walked substantially different tracks, at least in portions, going 'to' and 'fro' on our two reciprocal pairs. This was about the same for both pairs of segments even though they differed in their locations on campus and the longer pair of segments (B) was twice as long. This pattern was also replicated across both female and male participants. It is not obvious whether we should expect participants who had been on campus for a longer time—and were thus more familiar with its layout—to be more likely or less likely to take symmetric routes on reciprocal pairs. Knowing the campus better, including from more perspectives, suggests that one should be better able to choose optimal routes, which would be the same in both directions if based on variables like length or walking time. In contrast, one who knows the campus better should be better able to choose alternatives routes in reciprocal directions that were nearly equally as good as each other—they should be more competent at choosing asymmetric alternatives. In fact, we did not find a relationship between months on campus and tendency to choose asymmetrically. However, a large portion of our participants (40%) had been on campus for the same period of one year, so it would be valuable to test the route choices of participants with a much wider range of exposures to an environment. Finally, we found that the Asymmetry Indices for the two pairs of reciprocal segments were not significantly correlated across participants (if anything, even weakly negatively correlated). That is, we found no evidence that there is a *consistent* tendency or trait within individuals to take the same routes 'to' and 'fro' between a pair of nodes—we found no evidence for people being general symmetric or asymmetric route reversers.

Putting it all together, the design of our study and the way we calculated dissimilarity across participants gave us a unique approach to addressing whether the degree of choice asymmetry within participants we found could be explained as merely an expression of the degree of choice variability (dissimilarity) between participants. Since different participants walked different tracks from each other on a given segment, we might well expect a single participant to walk different tracks from themselves when traveling in the two directions of a single reciprocal pair. If this were true, it would suggest that the degree of choice asymmetry we found does not require explanation by any systematic tendency on the part of our participants to choose asymmetrically—baseline route-choice variability would naturally look like route-choice asymmetry when examined on reciprocal segments. To address this, we computed a third index we called Reciprocal Dissimilarity. It was just like the Dissimilarity Index calculated on every segment, but it was derived from comparing each participant's track on one segment of the reciprocal pairs to the tracks of all the other participants on that pair's segment in the opposite direction. When we compared this to the regular Dissimilarity Index, we found that the Reciprocal Dissimilarity Index was, in fact, greater than the regular Dissimilarity for both pairs of reciprocal segments, significantly so for Pair A and marginally so for Pair B. Thus, the tendency of participants to choose asymmetric routes in the two directions exceeded their natural tendency to choose variable routes on any segments.

4.1. Conclusions

Overall, we found significant asymmetry among routes in a naturalistic setting on a college campus. Interestingly, there was substantial variability of the kind of asymmetries people took; there was no individual tendency to take symmetric or asymmetric routes, nor was there a sex difference in route asymmetry. There was also no particular relationship with the amount of experience the navigators had with the campus, although our study's participants had a limited range of experience. Although participants demonstrated a degree of systematic asymmetry of choice on both of our two pairs of reciprocal route segments, they were much more consistent in their asymmetric choices on one pair than on the other.

There was substantial variation across participants in the route taken on each segment, but this natural variability did not entirely explain the asymmetries we observed on the two pairs of reciprocal segments. We observed variability in asymmetric choice that went over and beyond the natural tendency to vary routes in general. This is an important finding; future research should include having individuals walk the same segment multiple times (i.e., in the same direction) to acquire a direct assessment of within-person variability. Systematic analyses of how environmental features influence pedestrian route choice would also be valuable future research. Learning about the decision process that is involved in choosing consistent (or inconsistent) routes, along with the development of quantitative measures to characterize these choices, is an important first step in tackling the computational challenge of route choice.

Author statement

DRM: Conceptualization, Methodology, Software, Formal analysis, Writing - Original Draft, Writing - Review & Editing, Visualization, Supervision, Project administration. RCD: Investigation, Data Curation, Writing - Original Draft. MJ: Software, Validation, Formal analysis, Data Curation, Original Draft. ERC: Conceptualization, Methodology, Software, Formal analysis, Resources, Writing - Original Draft, Writing - Review & Editing, Visualization, Supervision, Project administration, Funding acquisition.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvp.2023.102004.

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