The Impact of Hills on Navigation

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Abstract

Navigation from origin to destination is a complex cognitive process; people employ a variety of strategies during navigation, both conscious and unconscious. The current studies investigated how hills affect navigation decisions. In Study 1, participants planned and walked routes along their college campus, which is dominated by a large hill. They were given different instructions and goals. Results revealed that participants selected routes that avoided the hill, even when this decision conflicted with task goals. In Study 2, participants were given route planning dilemmas; they were asked to choose routes for many different origin-destination pairs involving different types of terrain, either by free-recall of routes or by forced choice between two route options. Results revealed that participants preferred routes that are initially flat and encounter a hill later over routes that encounter a hill immediately. Findings from these studies indicate that the presence of hills can significantly impact decision making during navigation. Specifically, people prefer to avoid or minimize interaction with hills.

Introduction

Navigation

Consider a neighborhood you’re familiar with and imagine being asked to walk from one spot in the neighborhood to another. Chances are, you can decide on an effective route without much effort. But how do we arrive at this decision? What factors and mental processes are at play? Navigation is the process of moving from an origin to a destination. It requires people to evaluate environmental factors (roads, elevation, landmarks), apply spatial knowledge, consider different options, and decide on the best route (Bovy & Stern,1990; Golledge, 1995; Seneviante & Morrall, 1986). Navigation is a complex cognitive task, and people often employ strategies and heuristics, sometimes without awareness. For example, when given a choice between two equally efficient routes, one going north and the other going south, people show an unconscious preference for southern-going routes, potentially perceiving south as “downhill” (Brunye, Mahoney, Gardony, & Taylor, 2010; Brunye et al., 2012).

Overview

Whereas Brunye and colleagues (2010) identified a south-going bias due to perceived changes in elevation, the current studies investigate the effects of actual changes in elevation. Relatively limited research has examined how hills and slopes affect navigation. To explore this issue, we conducted studies using two different paradigms to investigate navigation strategies that involve moving around, up, and down hills. Both paradigms used an environment well-known to participants. The first study was exploratory, considering real-time navigation choices. In this study, participants planned and walked along routes on their college campus, which is dominated by a large hill. They did so with different instructions and goals. The second study evaluated participants' route selection decisions, in this same environment. Participants did not actually navigate, but instead decided between two roughly equal route choices. Across these studies, participants made route choices between various origin-destination pairs via free recall and forced-choice. The origin-destination pairs presented routes that interacted with the hill and terrain in different ways.

Background: Reference Frames and Heuristics

Many factors that affect navigation have been identified in the literature and are potentially relevant when approaching the question of how hills affect navigation. One factor that impacts navigation decisions is reference frame. There are different ways that people conceptualize their environments; when planning routes, people either assume an egocentric reference frame or an allocentric reference frame. An egocentric reference frame considers the environment from the ground, relative to the individual's position. An allocentric reference frame considers the environment from a bird's eye view (Klatzky, 1998). The perspective assumed by an individual can implicitly affect navigation in many ways (Taylor & Tversky, 1992; Taylor, Naylor & Chechile, 1999; Brunye et al., 2012; Wen & Kawabata, 2013). For example, the south-going bias identified by Brunye and colleagues (2010) is only present when people assume an egocentric reference frame. The present studies are designed to explore the effects of both egocentric and allocentric reference frames.

Another factor that impacts navigation is the use of unconscious cognitive heuristics. Cognitive heuristics are cognitive processes that are efficient but don't utilize all available information; they may be conscious or unconscious (Gigerenzer, & Gaissmaier, 2011). People may rely on cognitive heuristics to reduce cognitive load or make quick decisions under time pressure (Rieskamp & Hoffrage, 1999). Despite ignoring some information, cognitive heuristics generally result in accurate judgments and effective decisions (Gigerenzer, & Gaissmaier, 2011).

The south-going bias (Brunye et al., 2010) is one example of an unconscious heuristic people may use during navigation. Another heuristic involved with route planning shows that people prefer routes with fewer landmarks and turns (Sadalla & Staplin, 1980; Seneviante & Morrall, 1986). These are a few of many implicit strategies that may affect decision making during navigation but are outside of people's awareness. Numerous other such heuristics have been identified in previous research; these strategies have the most influence on decision making when there is no clearly optimal choice (Christenfield, 1995).

However, unconscious heuristics can also result in inaccurate and suboptimal navigation. People may rely on these strategies even when they result in counterintuitive and inefficient decisions. For example, people tend to falsely perceive routes with more turns to be longer; this is termed the *route-angularity effect* (Brunye et al, 2015; Sadalla & Magel, 1980). People may utilize *least-angle strategies* and avoid selecting routes that deviate from moving toward the destination (Conroy-Dalton, 2003). Further, people may employ *initial-segment strategies* and select routes based disproportionately on their initial straightness. *Initial segment strategies,* and other navigation heuristics, may represent an effort to reduce cognitive load by selecting a simpler route (Bailenson & Shum, 2000). Although people prefer to select routes that are initially straight over shorter routes, they are still able to select the shortest route when explicitly directed (Bailenson & Shum, 2000). Thus, such heuristics may not represent people's limited spatial processing ability but may instead represent a trade-off between the effort required to plan a route and the efficiency of a route (McNamara & Diwadkar, 1997; Bailenson & Shum, 2000).

Understanding the vast array of strategies involved in navigation presents valuable applications for predicting wayfinding behavior (Heth & Cornell, 1998; Raubal, 2002).

Objective

The current studies focus on how hills and terrain affect navigation. We attempted to identify key factors and heuristics at play with respect to navigation decisions with hills. Study 1 featured real-time navigation through actual changes in elevation while participants walked through their college campus. Whereas previous research has considered the effect of perceived hills in navigation planning (Brunye et al., 2010), to our knowledge this is the first study that investigates participants' physical navigation through hilled terrain in a controlled environment. We were interested in how real-time physical navigation might differ from solely navigational planning in terms of the strategies and heuristics utilized. In order to get at these questions, participants in study 1 were instructed with different navigational goals: either to select a complex route (as if they were giving a tour), or to select the most efficient route. These navigational goals facilitated the investigation of strategies and heuristics concerning route complexity and efficiency, for example the *route angularity effect* (Brunye et al., 2015; Sadalla & Magel, 1980) and *initial-segment strategies* (Bailenson & Shum, 2000).

However, study 1 featured only two origin-destination pairs through which participants navigated. In order to understand the factors affecting navigation through hilled terrain in a broader scope, study 2 presented participants with many different origin-destination pairs. These origins and destination were still all located on the participants' college campus, which is dominated by a large hill. Participants didn't physically navigate, but decided between route options for each origin-destination pair; the route options differed by direction and terrain, in order to reveal any directional or terrain preference heuristics such as the south-going bias identified by Brunye and colleagues (2010). Two such experiments were conducted in study 2, one where participants used free-recall to describe a route from origin and destination, and another where participants were forced to choose between two given options. The free-recall and forced-choice paradigms compared navigational choices from an egocentric vs. an allocentric reference frame, respectively. This was to investigate the potential impact of reference frame on navigation, demonstrated in previous studies (Taylor & Tversky, 1992; Taylor, Naylor & Chechile, 1999; Wen & Kawabata, 2013). Together, these studies provided a framework to explore navigation with respect to hills.

Study 1: Planning and Walking Routes

Methods

Participants

Thirty-three Tufts University undergraduates (27 female, M_{age}=20.7) participated for monetary compensation. Participants were third- and fourth-year students who were familiar with the campus layout. All participants completed a pre-screen survey. Participants provided informed written consent before the experiment began in accordance with the guidelines established by Tufts University's Institutional Review Board.

Materials

Pre-screen survey. The survey confirmed participants' familiarity with the campus and asked questions for demographic information, including gender, age, race, language proficiency, and handedness (right- or left-handed). The survey included a couple of questionnaires regarding spatial ability, including the Santa Barbara Sense of Direction Scale (SBSOD; Hegarty, 2002), and a Spatial Representation Questionnaire (SRQ; Pazzaglia, 2001).

Eye tracking. Recordings were performed using mobile eye tracking glasses, SMI ETG-1, at 30Hz recording speed. Three-point gaze calibration was performed using environmental references (trees and lampposts) as calibration points. The eye tracking glasses recorded participants' gaze, forward facing video, and audio. Participants were given a hat to prevent sunlight interference with the eye tracker. The current report focuses on route choices and does not analyze the eye tracking data collected.

Location. The experiment was conducted outdoors at Tufts University's Medford campus. The campus is approximately half a mile across and situated on a hill. There were three landmark locations relevant to the experiment: an uphill dining hall, a downhill dining hall, and the psychology department, also located downhill (see Figure 1).

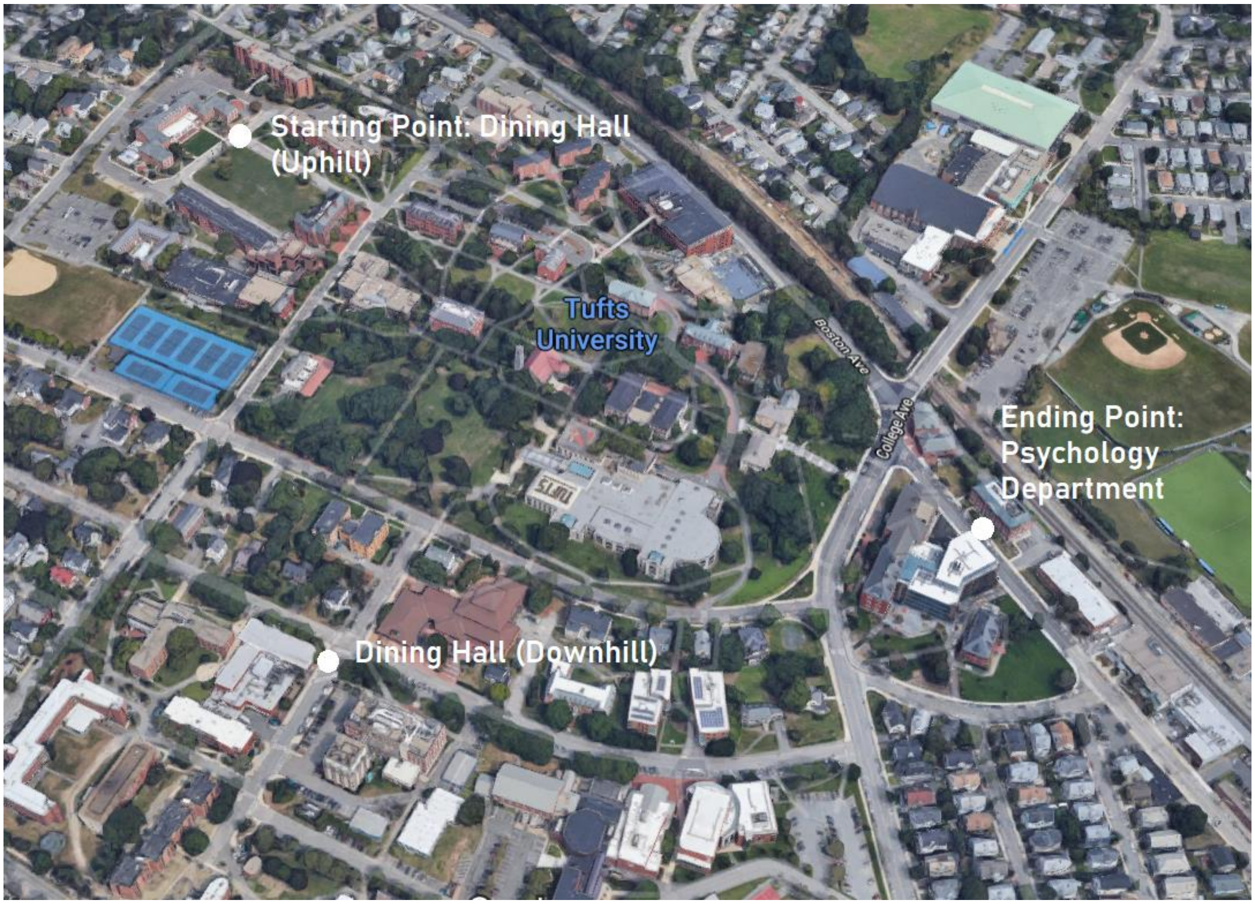

Figure 1. Map of Tufts University campus, important landmarks labeled.

Procedure

Participants were asked to plan and walk two routes through the campus. The first route, "route 1," was from the uphill dining hall to the downhill dining hall, so it necessarily involved going down the hill. The second route, "route 2," was from the downhill dining hall to the psychology department, also located downhill. All participants completed the routes in this order. These routes were selected to cover most of the campus, allowing for analysis of navigation through a varied and complex environment, including analysis of navigation with respect to the campus' hill. Participants were split into two experimental conditions and received one of two sets of instructions about how to plan their routes. In the "efficient first" condition, participants were told to plan the most efficient route for route 1, and for route 2 to plan a route as if they were showing a prospective student around. In the "tour first" condition, the order of these route planning instructions was switched. Conditions were counterbalanced across participants.

Before participating in the experiment, participants completed the pre-screen survey. They completed the survey in their own time via the SONA online research participation tool that they also used to sign up for the experiment. The starting point of the experiment session was located outside the dining hall on the uphill portion of the campus. The participants arrived and met the experimenter there. Upon arrival, participants provided informed consent, and were briefed about the experiment procedure. They were then introduced to a think-aloud protocol – participants were told that they were to verbalize all their thoughts for portions of the experiment, and that their verbalized thoughts would be recorded. The think-aloud task was used to provide insight into the participants' cognitive processes throughout the experiment. However, the current report focuses on route decisions and does not analyze the think-aloud data collected. Participants familiarized themselves with the think-aloud procedure by reasoning aloud through practice questions that were unrelated to the experiment's goals:

- *What is 12 times 18?*
- *How many windows were there in a house you used to live in, for example, your parents' house?*

Next, participants were told to navigate from the starting point to the dining hall located downhill. They were either told to simply take the most efficient route, or to take a route as if they were showing a prospective student around campus, depending on experimental condition. Participants were then asked to think-aloud while planning the route they would take. Participants were also asked to point in the direction of various landmarks on campus, despite being unable to see them directly. This task was administered to determine participants' spatial concept of the campus layout. Finally, participants were asked to walk the route they had planned, while thinking aloud for the duration of the walk. Audio, video, and eye gaze was recorded for each task (planning, pointing, and walking).

Upon arrival at the dining hall downhill, participants were instructed on the next portion of the experiment. They were asked to navigate to the psychology department. Again, participants were either told to simply take the most efficient route or to take a route as if they were showing a prospective student around campus. These task instructions were counterbalanced such that participants who were told to take the most efficient route in the first portion of the experiment were now told to take a route as if they were with a prospective student, and vice versa. Once more, participants were asked the think-aloud while planning their route, pointing to landmarks, and walking. After arriving at the psychology department, participants were debriefed and compensated for their time.

Results

Route Length Analysis

A mixed factor ANOVA with a route (2: route 1—uphill dining hall to the downhill dining hall; Route 2, downhill dining hall to psychology department) by instruction condition (2: "efficient first"; "tour first") design compared the length of participants' routes, as a measure of route efficiency. Route served as the within-participant variable and instruction as the between-participant variable. The analysis revealed no significant effects. There was a marginally significant interaction between route and instruction $F(1,33) = 3.999$, $p = 0.054$. Participants in the "efficient first" condition chose longer routes (M= 0.352 mi) for route 2 as compared to those in the "tour first" condition (M=0.443 mi); however, this effect was not present for route 1. In other words, participants instructed to give a tour for route 2 chose longer routes than those instructed to take the most efficient route, whereas route length did not differ by instruction condition for route 1.

Decision Point Analysis

We analyzed route complexity using actions taken at decision points. A decision point is as a junction or intersection where navigational uncertainty is presented (Burnett et al., 2001; Janzen et al., 2004). A mixed factor ANOVA with a route (2: route 1—uphill dining hall to the downhill dining hall; Route 2, downhill dining hall to psychology department) by instruction condition (2: "efficient first"; "tour first") design compared the actions taken by participants at decision points (2: went straight; took a turn). Route served as the within-participant variable and instruction as the between-participant variable. The analysis revealed a significant interaction between route and instruction condition $F(1,33) = 8.435$, $p = 0.007$. This effect was qualified by a significant three-way interaction between route, instruction condition, and decision point action F(1,33) = 5.996, p = 0.020. Participants in the "tour first" condition took more turns at decision points (M = 7.059), as compared to those in the "efficient first" condition (M=3.750) for route 1, however, this effect was not present for route 2. In other words, participants instructed to give a tour for route 1 chose routes with more turns than those instructed to take the most efficient route, whereas number of turns did not differ by Instruction for route 2. These results are depicted in Figure 2 below.

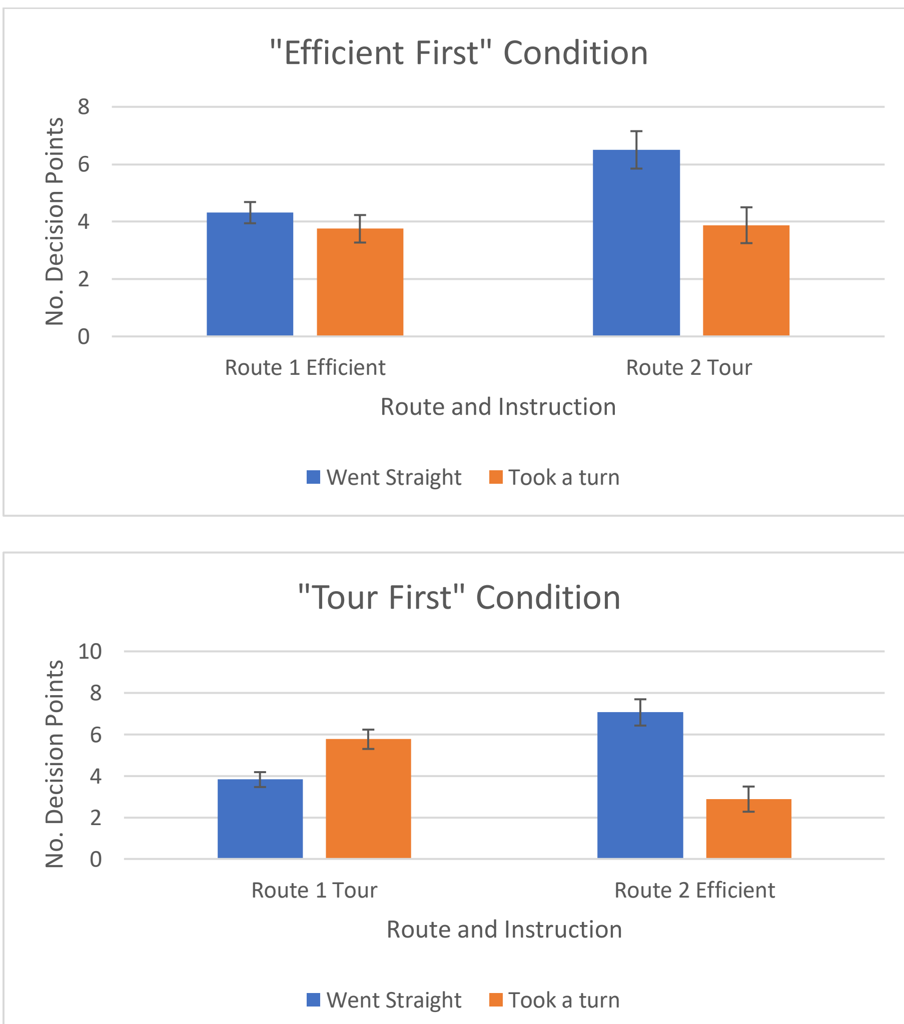

Figure 2. Three-way interaction between route, instruction condition, and decision point action. Error bars represent standard error.

Discussion

Study 1 revealed a three-way interaction between route, instruction condition, and decision point action. Participants instructed to give a tour selected routes with more turns than those instructed to take the most efficient route, but only for route 1; for route 2, the number turns did not differ by Instruction condition. Routes with more turns are perceived as longer and more complex (Sadalla & Staplin, 1980; Seneviante & Morrall, 1986), and so it's expected that participants instructed to give a tour would select a more complex route. So why didn't participants select more complex routes when instructed to give a tour for route 2?

To answer this question, we must consider the properties of route 1 vs. route 2. Route 1 originated at an uphill dining hall and terminated at a downhill dining hall. Participants were thus forced to navigate down a hill in order to complete route 1. By contrast, route 2 originated at the downhill dining hall, and terminated at the psychology department, also located downhill. In this case, there were multiple viable, but equally efficient (same length) routes from origin to destination, some of which involved navigating up and down a hill, and some of which contained entirely flat terrain. Further, the flat terrain options for route two were straighter and less complex than the hilled terrain options. So, the observed interaction could be explained by participants selecting the flat and straight route option regardless of Instruction condition (Bailenson & Shum, 2000).

Thus, as Brunye and colleagues (2010) identified a south-going bias due to perceived or assumed changes in elevation, these results potentially demonstrate a south-going bias due to avoidance of actual changes in elevation. More interestingly, this hill-avoidance bias seems to take precedence over the participants' task goals; they opt to navigate flat terrain over giving a more complete and complex tour as instructed. Although it's uncertain whether participants were conscious of this decision, these results nonetheless illuminate one way in which hilled terrain can significantly impact navigation decisions. Whether this hill-avoidance bias is conscious or unconscious, especially in opposition to task goals, requires further investigation.

However, this isn't the only potential explanation for the observed results. Previous research indicates that people use *least-angle strategies* (Conroy-Dalton, 2003), wherein they avoid movement that is not in the direction of the destination, and *initial-segment strategies* (Bailenson & Shum, 2000), wherein they opt for routes that are more initially straight. Both these strategies could contribute to participants' selection of flat terrain routes for route 2. Yet another possible explanation calls upon the fact that participants always navigated route 1 first, and route 2 second. Participants could have been physically tired after walking route 1, and thus opted for a straighter and less complex route for route 2, regardless of instruction condition. Although, the routes walked by participants were relatively short (less than 10 minutes of walking). Importantly, none of these explanations are mutually exclusive with a hill-avoidance bias, as multiple strategies and heuristics could have been jointly employed.

Notably, since participants physically navigated along their routes, they would clearly adopt an egocentric reference frame. The south-going bias due to avoidance of perceived hills (Brunye et al., 2010) was found to be present only when participants adopted an egocentric reference frame, and so reference frame may have an effect when it comes to the impact of actual hills on navigation. In order to explore the effect of reference frame, as well as to develop a broader and more generalizable understanding of how hills affect navigation, we can turn to the results of study 2.

Study 2: Route Planning Dilemmas

Methods

Study 1 examined only two specific routes. In order to understand navigation with hills in a more broadly generalizable context, study 2 presented participants with many different origin-destination pairs and route options. In these experiments, participants did not physically navigate, but simply selected routes for each origin-destination pair. Two experiments were conducted to consider navigation from two different reference frames. In experiment 1, participants freely recalled the routes they would take step by step, in order to induce an egocentric reference frame. In experiment 2, participants chose between two routes that passed by certain landmarks, in order to induce an allocentric reference frame.

Experiment 1: Free Recall of Routes

Participants

54 Tufts University undergraduate students (32 female; age M = 19.8) participated for monetary compensation or course credit. 25 participants were first-year students. The other 29 participants were juniors or seniors.

Materials and Design

The Tufts University Medford campus provided an appropriate environment to investigate route planning with terrain change. A total of 20 origin-destination pairs were selected from landmark buildings, according to our design, with any given landmark referenced no more than three times as an origin or destination. The study used a mixed-factor design of 2(terrain: flat, sloped) x 2(route dilemma: north/south, east/west, no dilemma) x 2(route version: A, B). Terrain and route dilemma were within participant factors and route version was a between participant factor. Participants were randomly assigned to route version A or version B, with 27 participants in each group. Version B swapped the origins and destinations of the version A routes (i.e., *tennis court* to *library* became *library* to *tennis court*). The origin-destination pairs varied by terrain (flat vs. sloped), and route dilemma type. There were three types of route dilemmas: north/south dilemma, east/west dilemma, and no dilemma. North/south dilemmas involved choosing between two equivalent length routes: a primarily north-going route and a primarily south-going route. East/west dilemmas involved choosing between a primarily east-going route and a primary west going route. No dilemma origin-destination pairs had a single clearly optimal route.

To explore the role of the physical hill in route choices, the east/west dilemma routes moved downhill from origin to destination in version A, and north/south dilemma routes moved uphill from origin to destination in version A. Since origins and destinations were swapped in version B, east/west dilemma routes moved uphill, and north/south dilemma routes moved downhill.

To further explore how terrain impacted route recall, sloped origin-destination pairs were further broken down by when the terrain change occurred along the route-- immediately or later. For "immediate" (IM) trials, participants encountered a hill immediately at the beginning of their routes. For "Stay" trials, the terrain stayed flat until encountering a hill. Both north/south and east/west dilemmas had "IM" and "Stay" trials. Again, since version B switched the origins and destinations, "IM" routes became "Stay" routes, and vice versa.

On flat terrain, four origin-destination pairs were developed for the east/west dilemma with roughly equivalent length east-going and west-going route options (M_E = 0.14mile, M_W = 0.15mile), and four origin destination pairs were developed for the north/south dilemma (M_N =

0.18mile, M_S = 0.15mile). For sloped terrain, the east/west dilemma (M_E = 0.23mile, M_W = 0.26mile) and north/south dilemma (M_N = 0.24mile, M_S = 0.22mile) each also included four origin-destination pairs. For both dilemma types, two of the four pairs were in the "Stay" condition, the other two pairs were in the "IM" condition. Finally, there were four origin-destination pairs with no dilemma (two with flat terrain and two with sloped terrain), for a total of 20 origin-destination pairs.

The current experiment used a free recall task, but the designated dilemma routes were the clearly optimal routes for each origin-destination pair. So, although participants could potentially recall other routes between origin and destination, this was unlikely. Figures below illustrate some example routes.

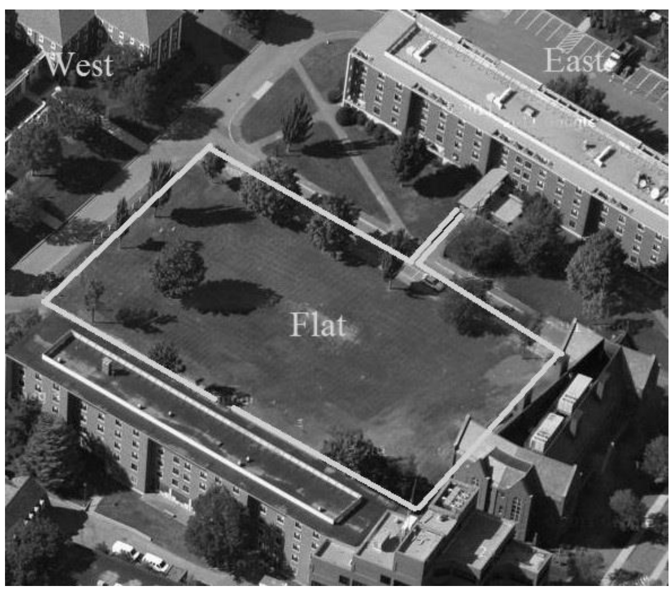

Figure 3. Example of route dilemma: flat, East/West dilemma.

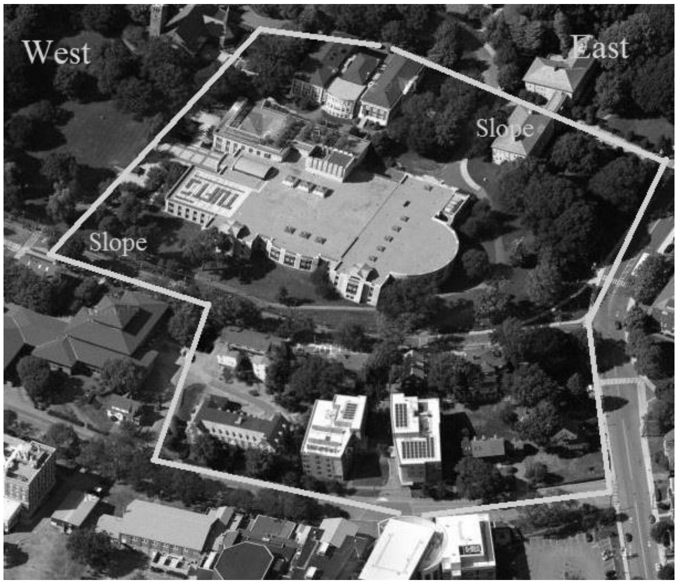

Figure 4. Example of route dilemma: sloped, East_IM/West_Stay dilemma.

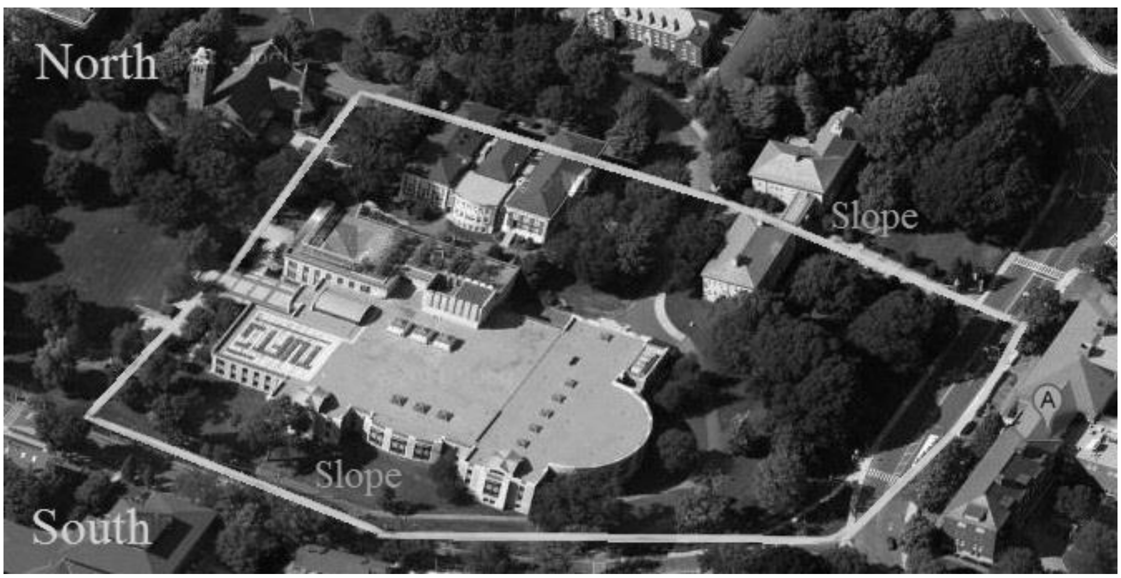

Figure 5. Example of route dilemma: sloped, North_IM/South_Stay dilemma.

Procedure

Following informed consent, participants sat before a Macintosh computer with a 19" monitor. They received 20 origin-destination pairs in succession and were asked to describe what they thought was the best route to get from origin to destination. They were instructed to include as many details as possible about their route, such as street names, building names, and which direction they would turn at intersections. One requirement for their descriptions was that the route must use already established roads and paths and could not "cut" through buildings or across grass. If a path the route took did not have a name or they could not recall the name, participants were told to clearly identify the buildings the route passes by. Participants were told that there was no correct answer, but to choose the route they considered "best". Participants recorded their route by typing on the computer.

Experiment 2: Forced Choice of Routes

Participants

Sixty-four Tufts University undergraduates (47 female; age *M* = 20.8) participated for monetary compensation or course credit. Thirty participants were first-year students, while the other 34 were juniors or seniors.

Design and Procedure

The design of Experiment 2 matched that of Experiment 1 but included an additional north/south dilemma for sloped terrain trials. In these trials, referred to as north_up/south_down and south_up/north_down trials, the northern route immediately moved uphill from origin to destination, and the southern route immediately went downhill from origin to destination, or the opposite was true. However, the current report focuses on navigation through "Stay" and "IM" hill terrains and does not include analyses of these trials.

Experiment 2 used a two-alternative forced choice task, instead of free recall. Following informed consent, participants sat at a 19" monitor connected to a Macintosh computer running Psychopy v1.76. Before the route selection task, a list of landmark names, which would be used as origins and destinations, was presented to participants. They recalled the location of each landmark and confirmed with experimenter if they could not recognize any of them. After this, they proceeded to the route choice task. Figure 6 illustrates the interface used to present the origin-destination pair and route options. Participants were instructed to choose the best route between the origin to the destination by pressing corresponding keys. The position of route options on the screen would switch between top and bottom and was counterbalanced across participants.

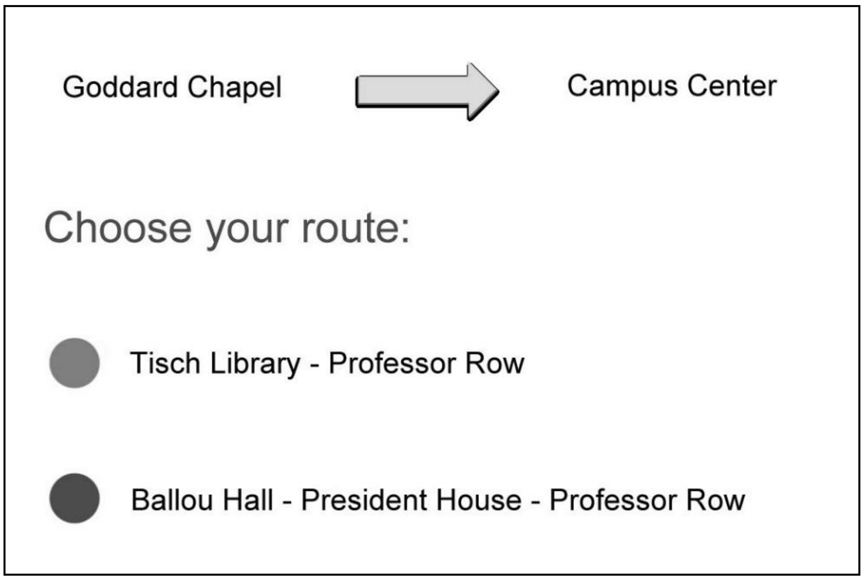

Figure 6. Example forced choice interface seen by participants

Results

Experiment 1: Free Recall of Routes

Flat Terrain Trials

Analyses compared the proportion of selected north-going vs. south-going routes, and east-going vs. west-going routes on Flat terrain trials across all participants. For both north/south and east/west dilemma trials, one-sample t-tests were used to compare the mean proportion of routes selected for each direction to 0.5 (theoretical expectation given no directional preference). Results indicated that participants selected significantly more north-going routes (90.3%) than would be expected given an assumption of no preference, $t(53) = 17.219$, $p < 0.001$. Results revealed no significant preference for east-going routes vs. west-going routes. These results are depicted in Figure 7 below.

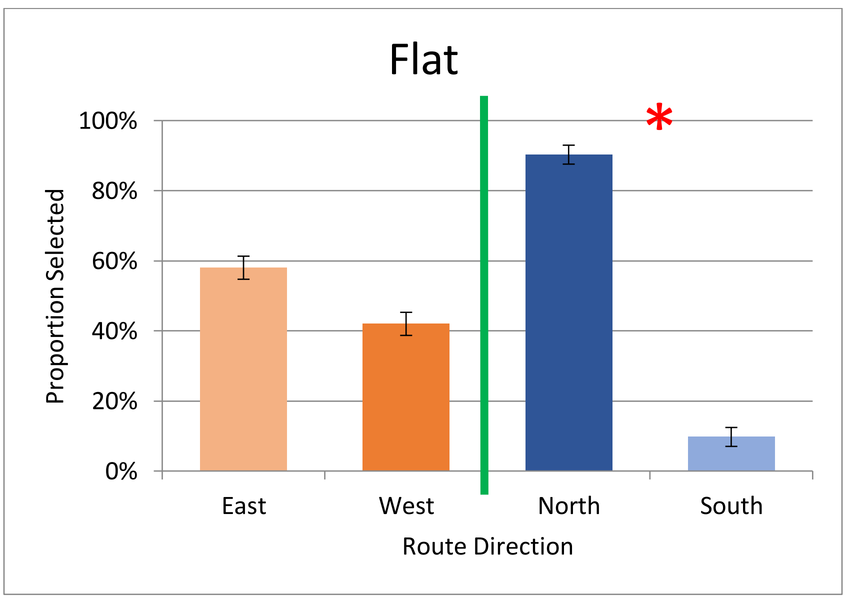

Figure 7. Results for Flat terrain trials of free-recall route dilemma experiment. Error bars represent standard error.

Sloped Terrain Trials: North/South Dilemmas

Analyses compared the proportion of selected north-going vs south-going routes on sloped terrain north/south dilemma trials across all participants. This comparison was broken out by hill direction (downhill; uphill) and terrain type (“IM” – hill encountered at start of route; “Stay” – route initially flat, but encounters hill later). For both downhill and uphill trials, one-sample t-tests were used to compare the mean proportion of routes selected for each direction and terrain type to 0.5. Results indicated that participants selected significantly more south-going “Stay” routes for downhill trials (70.5%), than would be expected given an assumption of no preference, $t(21) = 2.409$, $p = 0.025$. No other significant directional or terrain preferences were found. These results are depicted in Figure 8 below.

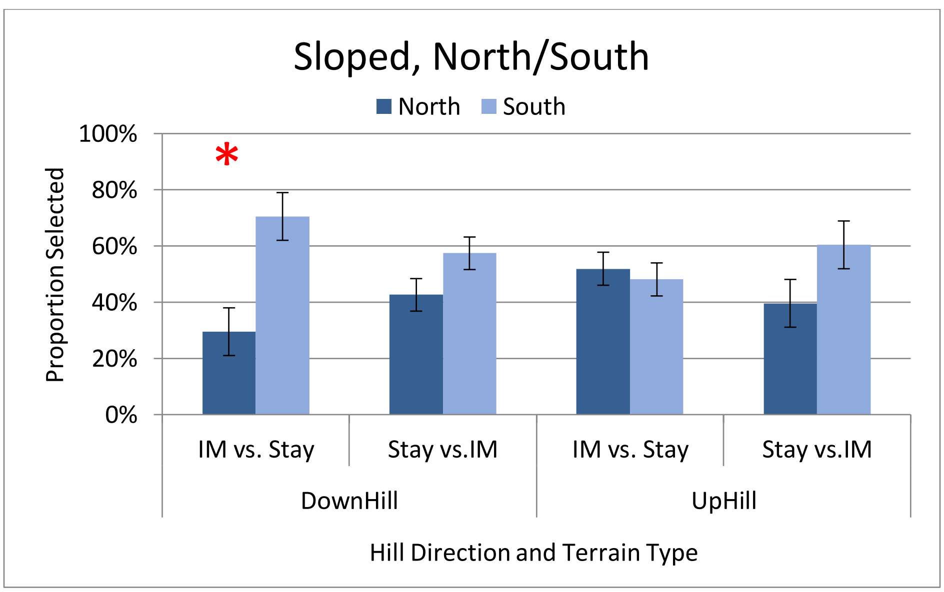

Figure 8. *Results for sloped terrain north/south dilemma trials of free-recall route dilemma experiment. Error bars represent standard error.*

Sloped Terrain Trials: East/West Dilemmas

Analyses compared the proportion of selected east-going vs west-going routes on sloped terrain east/west dilemma trials across all participants. This comparison was broken out by hill direction (downhill; uphill) and terrain type (“IM” – hill encountered at start of route; “Stay” – route initially flat, but encounters hill later). For both downhill and uphill trials, one-sample t-tests were used to compare the mean proportion of routes selected for each direction and terrain type to 0.5. Results indicated that participants selected significantly more east-going “Stay” routes for both downhill (66.0%) and uphill trials (95.8%) than would be expected given an assumption of no preference, $t(24)= 3.224$, $p - 0.004$; $t(23) = 11.000$, $p = 0.004$. Results also indicated that participants selected significantly more east-going “IM” routes for downhill trials (84.6%) than would be expected given an assumption of no preference, $t(25) = 4.797$, $p < 0.001$. No other significant directional or terrain preferences were found. These results are depicted in Figure 9 below.

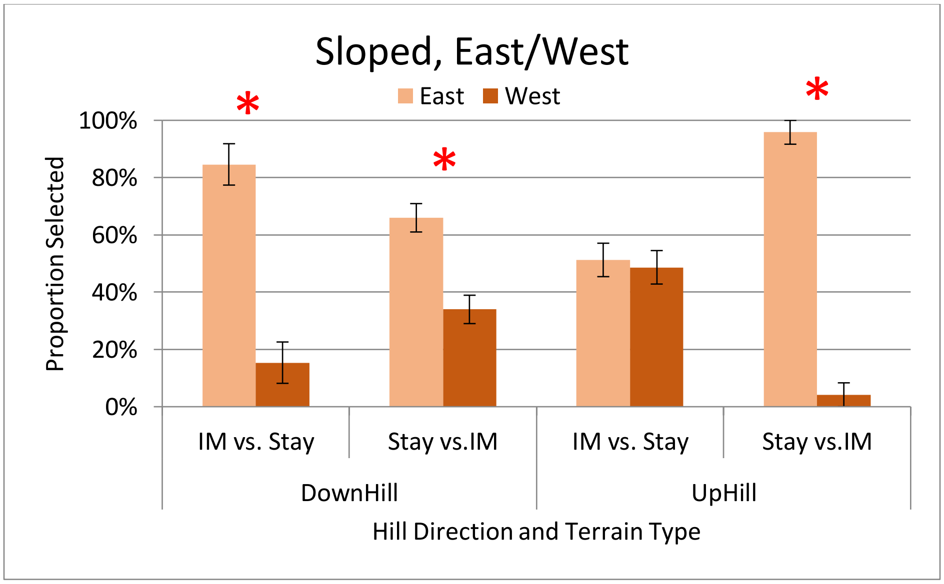

Figure 9. Results for sloped terrain east/west dilemma trials of free-recall route dilemma experiment. Error bars represent standard error.

Experiment 2: Forced Choice of Routes

The same analyses were conducted for the forced- choice paradigm as for the free-recall paradigm.

Flat Terrain Trials

Analyses compared the proportion of selected north-going vs south-going routes, and east-going vs. west-going routes on Flat terrain trials across all participants. For both north/south and east/west dilemma trials, one-sample t-tests were used to compare the mean proportion of routes selected for each direction to 0.5 (theoretical expectation given no directional preference). Results indicated that participants selected significantly more west-going (62.9%) routes than would be expected given an assumption of no preference, $t(63) = 3.914$, $p < 0.001$. Results also indicated that participants selected significantly more north-going routes (78.1%) than would be expected given no directional preference, $t(63) = 10.420$, $p < 0.001$. These results are depicted in Figure 10 below.

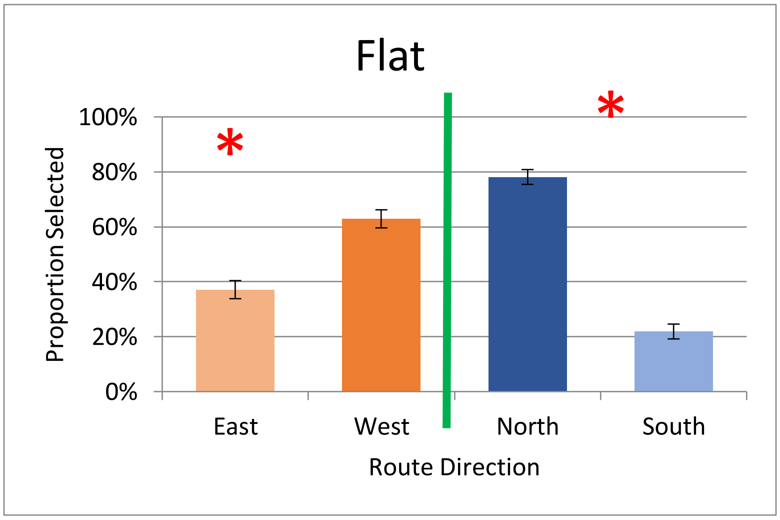

Figure 10. Results for Flat terrain trials of forced- choice route dilemma experiment. Error bars represent standard error.

Sloped Terrain Trials: North/South Dilemmas

Analyses compared the proportion of selected north-going vs south-going routes on sloped terrain north/south dilemma trials across all participants. This comparison was broken out by hill direction (downhill; uphill) and terrain type ("IM" – hill encountered at start of route; "Stay" – route initially flat, but encounters hill later). For both downhill and uphill trials, one-sample t-tests were used to compare the mean proportion of routes selected for each direction and terrain type to 0.5. Results indicated that participants selected significantly more north-going "Stay" routes for uphill trials (62.9%), than would be expected given an assumption of no preference, t(30)= 2.108, p = 0.043. No other significant directional or terrain preferences were found. These results are depicted in Figure 11 below.

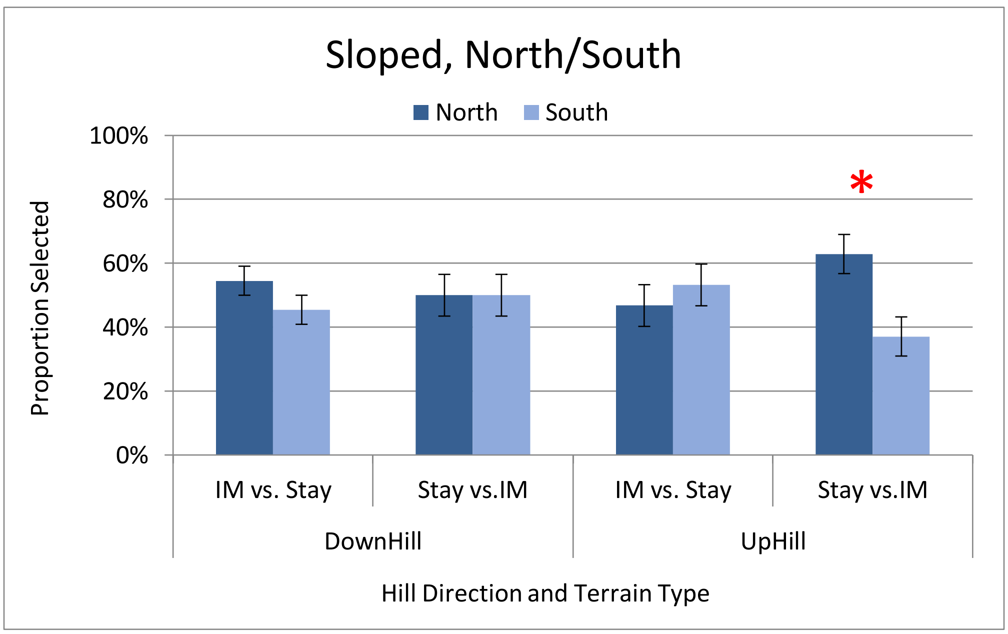

Figure 11. Results for sloped terrain north/south dilemma trials of forced- choice route dilemma experiment. Error bars represent standard error.

Sloped Terrain Trials: East/West Dilemmas

Analyses compared the proportion of selected east-going vs west-going routes on sloped terrain east/west dilemma trials across all participants. This comparison was broken out by hill direction (downhill; uphill) and terrain type (“IM” – hill encountered at start of route; “Stay” – route initially flat, but encounters hill later). For both downhill and uphill trials, one-sample t-tests were used to compare the mean proportion of routes selected for each direction and terrain type to 0.5. Results indicated that participants selected significantly more east-going “Stay” routes for both downhill (77.4%) and uphill trials (72.7%) than would be expected given an assumption of no preference, $t(30)= 4.894$, $p < 0.001$; $t(32) = 4.629$, $p =<0.001$. No other significant directional or terrain preferences were found. These results are depicted in Figure 12 below.

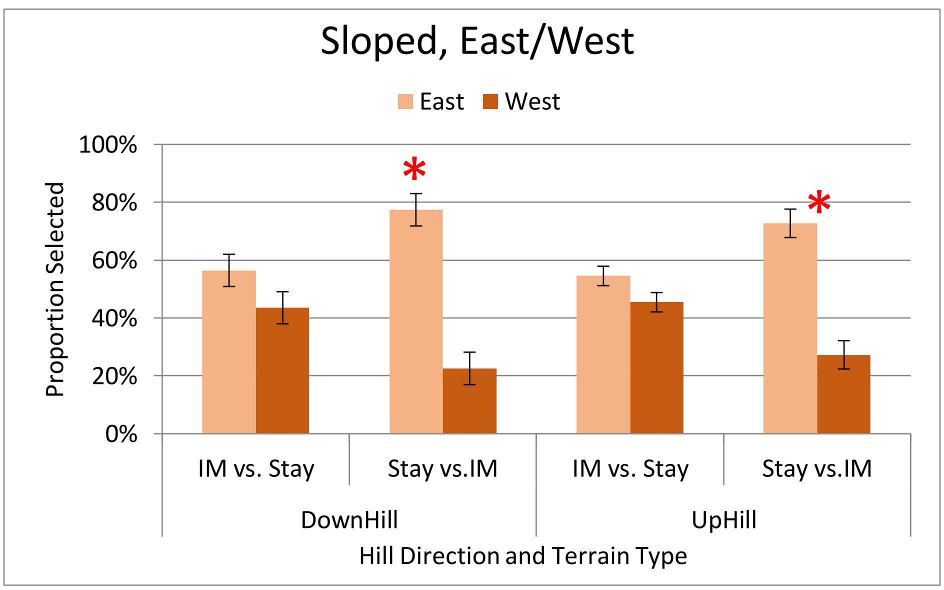

Figure 12. Results for sloped terrain east/west dilemma trials of forced- choice route dilemma experiment. Error bars represent standard error.

Discussion

Flat Terrain Trials

In the free-recall experiment, participants showed a preference for northern-going routes over southern-going routes on flat terrain. In the forced- choice experiment, there was also a preference for northern-going routes on flat terrain, as well as a preference for western-going routes over eastern-going routes, which was not present in the free-recall experiment. The free-recall experiment instructed participants to narrate step by step the route that they would take, leading to a first-person perspective. The forced- choice experiment allowed participants to choose between routes passing by different landmarks, leading to consideration of the campus layout from a bird's-eye view. Thus, the former would likely induce an egocentric reference frame while the latter would likely induce an allocentric reference frame. (Klatsky, 1998; Brunye et al., 2012).

The observed results demonstrate an overall north-going preference on flat terrain, regardless of reference frame. This is contrary to previous findings of a south-going preference exclusive to an egocentric reference frame (Brunye et al., 2010). However, those findings were with an unfamiliar environment, with no changes in terrain specified. In the current study, participants were familiar with the environment and knew that the terrain would be flat. Thus, any south-going bias due to perceived or assumed hills should not be present. These results potentially indicate that people simply have a north-going preference given flat terrain. These findings are difficult to explain and warrant further investigation. However, there was also a potential oversight in experimental design; although for these north/south dilemmas, the northern and southern options were roughly equal length, the southern routes were generally located along the rarely trafficked southern edge of the college campus. By contrast, the northern routes are frequently trafficked and passed through the campus, potentially making them more popular or familiar to the student participants.

The results also demonstrate a west-going preference, but only when adopting and allocentric reference frame. This potentially indicates that people simply prefer western-going when considering navigation from an allocentric reference frame. The effect likely isn't related to perceived changes in elevation, since such effects have only been found with egocentric reference frames (Brunye et al., 2010). Confirmation and an explanation for this west-going preference simply requires further research.

Sloped Terrain Trials

In the free-recall experiment, participants showed a preference for south-going "Stay" terrain routes when moving downhill, east-going "Stay" routes when moving uphill, east-going "Stay" routes when moving downhill, and east-going "IM" routes when moving downhill. In the forced-choice experiment, participants showed a preference for north-going "Stay" routes when moving uphill, east-going "Stay" routes when moving uphill, and east-going "Stay" routes when moving downhill.

Taken together, these results indicate an overall preference for "Stay" terrain over "IM" terrain. That is, participants prefer routes that are initially flat, but encounter a hill later, over routes that encounter a hill immediately. This could reflect a similar heuristic as *initial segment strategies* (Bailenson & Shum, 2000), wherein people disproportionately prefer routes which are initially straight. It could also be the case that people prefer routes that are initially flat. Like *initial segment strategies,* this could represent an effort to select simpler routes to reduce cognitive load (McNamara & Diwadkar, 1997; Bailenson & Shum, 2000). People may also be characterizing routes disproportionately by the characteristics of their initial segments, thus causing them to perceive immediate changes in elevation as hillier.

Comparing results between the free-recall and forced-choice experiments, it's difficult to discern whether reference frame has a concrete effect on what types of terrain people prefer. Notably, the only case of preference for "IM" terrain over "Stay" was a preference for east-going "IM" routes while moving downhill, assuming an egocentric reference frame. Still, it's unclear why this is the case, and further investigation is needed for a satisfactory explanation. Overall, analyses of Study 2 prove to be underdeveloped for providing data and explanations for any observed navigational differences between egocentric and allocentric reference frames. In the future, a more robust analysis, perhaps considering the collected think-aloud data to understand participant motivation, would be useful in determining the effects of reference frame on navigation with respect to hills.

General Discussion

The present studies were conducted to investigate the effects of hills on navigation decisions. Study 1 revealed a potential hill-avoidance bias; participants preferred a flat terrain route over a hilled terrain route, even though this conflicted with experimental task goals. Study 2 revealed a preference for routes that are initially flat and encounter a hill later over routes that encounter a hill immediately. The preference for initial route flatness observed in Study 2 could contribute to the effect seen in Study 1, wherein people selected straight, flat routes even though it conflicted with their task goal; those flat routes were selected over other routes which would have required participants to immediately navigate a hill. Conversely, the hill-avoidance bias observed in Study 1 could contribute to effect seen in Study 2. A preference for "Stay" terrain potentially indicates an effort to delay interaction with hilled terrain due to the hill-avoidance bias. These results come together to illustrate how the presence of hills can impact decision making during navigation. Namely, people tend to avoid or minimize interaction with hills during navigation. Further analyses of other data collected in these studies but not analyzed in this report, like eye-tracking and think-aloud data, may be valuable in yielding a more complete understanding of the observed results. In general, further research on the topic is needed to illuminate how hills impact navigation in different ways.

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