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How Do (Some) People Make a Cognitive Map? Routes, Places, and Working Memory

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Research on the existence of cognitive maps and on the cognitive processes that support effective navigation has often focused on functioning across individuals. However, there are pronounced individual differences in navigation proficiency, which need to be explained and which can illuminate our understanding of cognitive maps and effective navigation. Using a virtual environment involving 2 routes (Virtual Silcton, a desktop virtual environment; Weisberg, Schinazi, Newcombe, Shipley, & Epstein, 2014), we divided people into 3 groups based on their within-route and between-route pointing accuracy: integrators, non-integrators, and imprecise navigators. In Study 1, we found that imprecise navigators have lower spatial and verbal working memory, which may limit their ability to build accurate within-route representations. We also found that integrators maintain excellent memories of buildings as categorized by route membership, possibly supporting the idea of hierarchical representations of the environment. In Study 2, we assessed preferences regarding place and route learning using a virtual version of the rodent T-maze (Marchette, Bakker, & Shelton, 2011). Integrators found more goals overall, and although they did not have an overall preference for a place-based strategy, integrators who did choose a place-based strategy found more goals. The opposite was true for imprecise navigators. In Study 3, we added a monetary incentive for accuracy to evaluate whether increased motivation leads to fewer participants classified as imprecise, but found no significant change in the distribution of performance. These data have theoretical implications for the cognitive map hypothesis, and practical implications for improving navigational functioning. A one-size-fits-all approach may fit none.

Keywords: navigation, virtual environments, individual differences, working memory, spatial cognition

Getting lost is costly. Yet individuals differ widely in how accurately they can represent and learn large-scale environments. There is a wide range, from expert navigators (Maguire, Woollett, & Spiers, 2006) to people who are severely navigationally impaired (Iaria & Barton, 2010), with many points in between (e.g., Hegarty, Richardson, Montello, Lovelace, & Subbiah, 2002; Ishikawa & Montello, 2006; Weisberg, Schinazi, Newcombe, Shipley, & Epstein, 2014). Such variation, and the existence of people who have difficulty with finding their way or who can only do so using familiar routes, might seem to undermine Tolman's (1948) proposal that all mobile organisms navigate using cognitive maps (i.e., spatial representations that contain qualitative metric information about large-scale environments, and which can be used to generate novel shortcuts or to take detours). Indeed, controversy has long surrounded the idea of the cognitive map, with studies of humans and nonhuman animals sometimes suggesting that spatial representations are fragmented and even incoherent (e.g., Foo, Warren, Duchon, & Tarr, 2005; Shettleworth, 2009). There is, however, another way to view human variation in navigation and its implications for the cognitive map controversy. Perhaps people have the potential to form integrated spatial representations, but this potential is demanding of cognitive resources, rather than automatic, and thus difficult to realize and often not fully developed—that is, some people form and use cognitive maps, whereas others do not (Weisberg et al., 2014).

Offering the answer "It depends" is only an interim solution; however, because it clearly invites the further question "On what?" Answering this question has practical as well as theoretical importance, because knowledge of the requisite cognitive skills and strategies would offer potential clues concerning how to go about improving navigational proficiency. Furthermore, from a theoretical point of view, the answer to this question has implications for how we characterize representations of the spatial environment. The term "cognitive map" has been criticized for implying a completely unified representation in which all possible spatial relations are represented equivalently (Downs, 1981). An alternative is a hierarchical representation, in which local areas, or par-

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ticular routes, are represented in detail, with the relations among them represented more coarsely (Chrastil & Warren, 2014; Jacobs & Menzel, 2014; Jacobs & Schenk, 2003; Kuipers, 2000; Wolbers & Hegarty, 2010).

One method for investigating how people form cognitive maps, specifying what such maps might represent, and specifying how people differ, is the *route integration paradigm* (Ishikawa & Montello, 2006). Participants learn the names and locations of distinctive places along two separated routes. They are then exposed to a connecting route that provides information about how the two routes are related. Subsequent tasks tap the participants' knowledge of the locations within and between the two routes. In a real-world setting in which participants were driven along routes, Ishikawa and Montello (2006) found very substantial individual differences that correlated with self-reported navigation ability. Some people related the two routes effectively, immediately, and seemingly easily; some people learned to relate the routes over time; and some people never integrated in the course of the experiment.

Using a similar layout, but in a walking environment that allowed for active rather than passive movement, Schinazi, Nardi, Newcombe, Shipley, and Epstein (2013) also found substantial individual differences, although variation was most marked before participants experienced the connecting route. Performance on the route integration paradigm, after the connecting route was traversed, correlated with hippocampal volume, supporting in unselected subjects what Maguire and colleagues (2006) found in London taxi drivers. Schinazi and colleagues also found that the relation was mediated by variation in perspective-taking skills assessed on a paper-and-pencil test.

However, experimentation in a real-world environment, whether experienced by driving or by walking, poses formidable practical challenges that limit sample size, and hence makes it difficult to investigate individual differences in depth. Therefore, Weisberg et al. (2014) devised a virtual learning environment modeled after the real-world one used by Schinazi et al. (2013). Individual differences emerged for both within- and between-route judgments, and a cluster analysis based on between- and within-route pointing scores suggested the existence of three groups. One group, *integrators*, performed well on both within- and between-route judgments. A second group, *non-integrators*, performed well on within-route judgments, but poorly on between-route judgments. A third group, *imprecise navigators*, performed poorly (although above chance) on both types of pointing judgments.

Learning in the desktop virtual environment, Virtual Spatial Intelligence and Learning Center Test of Navigation (Virtual Silcton, Weisberg et al., 2014) Virtual Silcton thus potentially provides a practical technique for gathering data on large enough samples to study individual differences, and to investigate the implications for the idea of a cognitive map. But adopting a three-group classification to characterize performance in the route integration paradigm needs further exploration before its validity and utility can be assumed. One question that can be raised is whether integrators simply perform well on a wide variety of cognitive tasks. Integrators certainly seem to do better on a variety of navigation-related spatial measures, but the picture on measures not closely related to navigation is unclear (Weisberg et al., 2014). Although participants reported similar levels of verbal ability and small-scale spatial ability, self-report scales are limited on their own (e.g., integrators may actually be better at verbal tasks, but self-report more modestly). Here, we have included outcome measures that tap spatial knowledge (an onsite pointing task and a model-building task), and outcome measures that tap nonspatial knowledge (a building naming task and a route membership task, described further in the Method Sections) to determine whether non-integrators and imprecise navigators learn different aspects of the environment than we measured previously. We have also included a widely used measure of verbal intelligence to determine whether differences on the navigation task are attributable to general differences in intelligence. A second issue is whether the distinction between non-integrators and imprecise navigators is an important one. Does the more accurate within-route pointing of the non-integrators indicate an important step toward to construction of integrated representations across routes? What is the nature of such integrated representations? Do the same processes that facilitate within-route accuracy underlie between-route accuracy, or do these processes differ? An alternative way to conceptualize the postulated difference between non-integrators and imprecise navigators is to suggest that the self-reports of these two groups are accurate, and that, in fact, there is no need to regard people who vary along a continuum of within-route accuracy as fundamentally distinct.

In a series of three studies, we investigated the validity of the three-group classification, the correlates of group membership, and the implications of the findings for cognitive map theory. We chose individual difference variables for the first two studies from among the set of possible correlates of navigation proficiency based on a recent review of navigational abilities (Wolbers & Hegarty, 2010). In all studies, we also included a measure of verbal intelligence, to allow us to determine whether group differences are attributable to navigation-specific differences or are correlated with general intelligence. We introduce each variable in more detail in the Method sections, but, in overview, Study 1 examined the nature of the relation between within- and between-route representations, and the role of verbal and spatial working memory in building each, and Study 2 investigated place and response learning preferences. In Study 3, we sought to address the possible effect of motivation. Finally, using the cumulative data set of almost 300 participants in these three studies, together with data from Weisberg et al. (2014), we examined the statistical justification for a three-group classification and individual difference measures that had been gathered across all studies (e.g., the Santa Barbara Sense of Direction Scale [SBSOD], the Mental Rotation Test [MRT], the Spatial Anxiety Questionnaire [SAQ]). This latter analysis also includes individual difference measures, including a measure of verbal intelligence, to allow us to determine whether group differences are attributable to navigation-specific differences or could simply be attributed to general intelligence.

Study 1: The Role of Working Memory Capacity and Categorical Storage

The underlying rationale for the three-group classification is theoretical, and derives from the decades-old proposal that route memory is prerequisite to the formation of cognitive maps (e.g., Allen, Kirasic, Dobson, Long, & Beck, 1996). However, this conceptualization never specified exactly what the subsequent step of constructing survey representations (or cognitive maps) entailed. It was often implied that these representations were truly integrated, but an alternative is that the routes are interrelated hierarchically and people then make accurate inferences between routes based on this representation, as suggested by some recent models (Chrastil & Warren, 2014; Jacobs & Menzel, 2014; Jacobs & Schenk, 2003; Kuipers, 2000; Wolbers & Hegarty, 2010). Study 1 was designed to address this idea by evaluating whether integrators retain strong memories of route membership. If so, one interesting implication is that non-integrators differ importantly from imprecise navigators, even though they reported feeling the same about their sense of direction and did not differ in spatial skills in Weisberg et al. (2014). They have at least succeeded in accurately encoding within-route relations, the initial step required for successful integration.

Additionally, Study 1 aimed to explore whether cognitive capacity was equally involved in within- and between-route learning. In a review of the cognitive processes underlying effective navigation, Wolbers and Hegarty (2010) discuss the importance of executive function and working memory processes that transform various spatial cues into stable spatial representations. The route integration paradigm requires encoding, storage, and active manipulation and inference processes regarding buildings' names, appearances, and spatial positions encoded relative to a variety of cues. There is already some evidence from interference paradigms that good and poor navigators engage different working memory processes to encode and store information about large-scale environments (Ploran, Rovira, Thompson, & Parasuraman, 2015; Wen, Ishikawa, & Sato, 2011, 2013). However, this prior research has not differentiated between learning individual routes and integrating between them. This distinction is important both because individuals differ on both types of tasks, and because the two tasks may tap distinct cognitive processes. Working memory resources may be more important for one than the other. Investigation of this issue requires looking at both spatial and verbal working memory. Although it might seem natural to suggest that spatial working memory is more important for a spatial task, navigation also often requires learning the names of buildings and streets, so verbal working memory may also be important.

Method

Participants. Participants were recruited using one of two methods with the aim of collecting approximately 25 participants per navigation group. Eighty participants were initially recruited for a one-session study in exchange for $10 cash with the possibility of follow-up later in the semester, if they agreed, in exchange for another $10. Of this set, 30 participants completed two sessions and were included in the final sample. Because of the high dropout rate, we changed the method of recruitment. Fifty-one participants were recruited to participate in a two-part study in exchange for class credit or $20 cash. Five participants had to be dropped because they either did not return for Part 2 or because data were lost for technical errors. Participants who did not complete the study, recruited using either method, were significantly worse on within-route pointing compared with participants who completed both parts, $t(128) = 2.08$, $p = .047$, $d = 0.36$. Because this was the only difference (which would not have survived multiple comparisons of the 10 measures we conducted this analysis on), we decided to include all participants for whom we had data from both parts of the study in the final sample. The resulting sample consisted of 76 college undergraduates (46 female). Of those, 57 self-reported being native English speakers. Seven participants were Asian, 11 were Black, 41 were White non-Hispanic, four also reported being Hispanic, and 14 either reported "Other" or did not report race or ethnicity.

Measures.

Demographics. The demographics and self-report data were ethnicity, sex, handedness, education level, vision, and an fMRI screener including questions about pregnancy, metal in the body, and neurological disorders (for follow-up studies with fMRI not reported here).

SBSOD (Hegarty et al., 2002). This self-report measure of navigation ability consists of 15 7-point Likert-scale items, such as "I am very good at giving directions" and "I very easily get lost in a new city." The average score for each participant has been shown to correlate highly with performance on behavioral navigation tasks in real and virtual worlds (Hegarty et al., 2002; Weisberg et al., 2014), and with individual differences in neural structure and function (e.g., Epstein, Higgins, & Thompson-Schill, 2005; Schinazi et al., 2013). The SBSOD will be reported in conjunction with the Study 2 and 3 results.

SAQ (Lawton, 1994). This self-report measure of spatial anxiety consists of seven 7-point Likert-scale items that ask participants to indicate their level of anxiety when confronting situations, such as "Locating your car in a very large parking garage or parking lot" and "Finding your way to an appointment in an area of a city or town with which you are not familiar." The SAQ findings will also be reported in conjunction with the Study 2 and 3 results.

Virtual Silcton (Schinazi et al., 2013; Weisberg et al., 2014). Virtual Silcton is a behavioral navigation paradigm administered via desktop computer, mouse, and keyboard. Modeled after the route integration paradigm (e.g., Hanley & Levine, 1983; Holding & Holding, 1989; Ishikawa & Montello, 2006; Schinazi et al., 2013), participants learn two routes in separate areas of the same virtual environment by virtually traveling along a road indicated by arrows (see Figure 1). They learn the names and locations of four buildings along each of these routes. Then, they travel along two routes which connect the sets of buildings from the first two routes. Virtual travel consisted of pressing arrow keys on a standard keyboard to move in the environment, and the mouse to look around. Participants were bound to travel only along routes indicated by arrows by invisible walls, but could move and look at whatever pace they chose. Each route was traveled once, minimum, from the beginning to the end and back to the beginning, although participants could take as much time as they liked. Buildings were indicated by blue gems, which hovered over the path, and were named with signs in front of the building.

Participants were tested on how well they learned directions among the buildings within one of the first two routes, and among buildings between the first two routes. Testing involved two tasks. For an onsite pointing task, participants pointed to all buildings from each building they learned. The participant viewed the virtual environment along the route, next to one of the buildings they learned, and moved the mouse to rotate the view and position a crosshair toward one of the other buildings, then clicked to record the direction. The name of the building at the top of the screen then

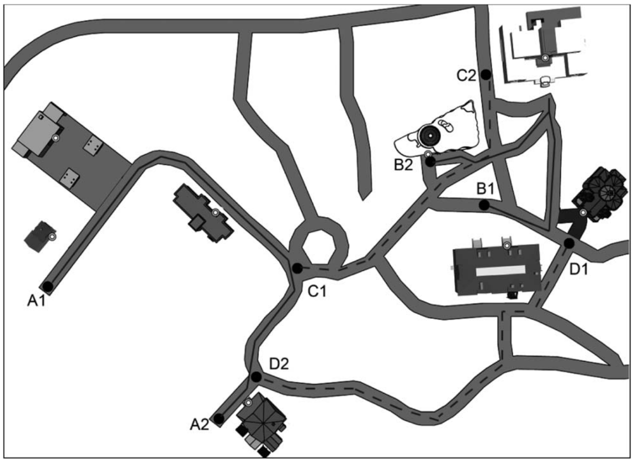

Figure 1. Aerial view of Virtual Silcton with main and connecting routes (from Weisberg et al., 2014). An aerial view map depicts the layout of buildings, main routes, and connecting routes for the virtual environment. Note that the spatial arrangement of buildings was identical to a real-world environment (used in Schinazi et al., 2013). The letter–number combinations indicate starting and ending points along each of the routes learned. All participants began each route at 1, traveled the entire route to 2, and walked back to 1. Participants always learned the main routes (solid lines) first, but Route A and Route B were counterbalanced between participants. Then participants learned both connecting routes (dashed lines), and Route C and Route D were similarly counterbalanced.

changed, and the participant pointed to the next named building. The dependent variable is the (absolute, not signed) error between the participant's pointing judgment and the actual direction of the building (if this difference was greater than 180°, it was corrected to measure the shorter of the two possible arcs), which is measured for within-route trials and between-route trials separately. This resulted in 32 between-route trials and 24 within-route trials. Of the 24 within-route trials, 14 were mutually intervisible (defined strictly as any part of the building in view), whereas 10 were not. Participants also completed a model-building task wherein they viewed a rectangular box on a computer screen and birds-eye-view images of the eight buildings. Scrolling over the buildings with the mouse pulled up a picture of the front view of the building and its name. Participants were instructed to drag and drop buildings to the position in the box they believed the building would be located (as if they were creating a map), without regard to the orientation of the buildings or to the map. (Results are largely redundant with the pointing task, but see Tables 1 and 2, as well as The Overall Pattern: Analyses Across Data Sets section for detailed results). The model-building task was scored using bidimensional regression analyses (Friedman & Kohler, 2003).

Spatial and verbal working memory complex span (symmetry span and operation span; Unsworth, Heitz, Schrock, & Engle, 2005). These measures of complex working memory interleave two tasks. For the spatial span task, participants view one red square in a 4 × 4 matrix of otherwise white squares, which they must remember the location of. They then must judge whether a separate array of black and white squares is bilaterally symmetrical or not. After a series of between three and five items (e.g., red square, symmetry judgment, red square, symmetry judgment), participants must recall the red-square locations in the correct order. Participants' scores are calculated by summing all correctly recalled items. The verbal span task is identical, but instead of a red square, participants view a letter that they must remember. Instead of a symmetry judgment, they solve a simple math equation and respond to indicate whether the equation is true or false.

Wide Range Achievement Test, Word Reading Subtest (WRAT-4; Wilkinson & Robertson, 2006). The WRAT-4 Word Reading Subtest is a measure of verbal IQ that correlates very highly with the Wechsler Adult Intelligence Scale (WAIS-III; Wechsler, 2008), and Wechsler Intelligence Scale for Children (WISC-IV; Wechsler, 2003) (Strauss, 2006). The WRAT-4 Word Reading Subtest requires participants to pronounce 55 individual words. Each participant's score is the number of words pronounced correctly out of 55.

Building Cued Recall Task. For this measure, participants were shown images of the eight buildings from Virtual Silcton and asked to type the name of the building as accurately as possible. This measure was scored in a strict form (building name must be exactly correct, with only minor spelling errors; e.g., "Sour" instead of "Sauer") and a loose form (building name must be uniquely interpretable as the correct building by the coder; e.g., "Museum" would be acceptable for "Tobler Museum," as there was only one building with museum in the name, but "Hall" would not be acceptable because there were two halls). Results did not differ between the coding forms, so only the loose coding was used. The two different recruiting methods meant that participants recruited for the single session study and asked back for part two voluntarily had between 1 and 5 weeks, whereas participants

Table 1
Working Memory and Pointing Correlations

Measure	1	2	3	4	5	6	*M*	*SD*
1. Within-route pointing	—	—	—	—	—	—	23.12	10.68
2. Between-route pointing	$.45^{**}$	—	—	—	—	—	44.36	13.85
3. Spatial working memory	$-.30^{**}$	−.15	—	—	—	—	30.03	8.27
4. Verbal working memory	$-.37^{**}$	−.20	$.57^{**}$	—	—	—	58.14	13.58
5. Route membership task	$-.50^{**}$	$-.36^{*}$	$.38^{*}$	$.40^{**}$	—	—	51.60	11.98
6. Model building–within	$-.68^{**}$	$-.48^{**}$	$.27^{*}$	.20	$.57^{**}$	—	.65	.23
7. Model building–total	$-.45^{**}$	$-.56^{**}$	.12	.22	$.28^{*}$	$.47^{**}$	.47	.27

Note. Model building–total is the bidimensional correlation coefficient for all eight buildings. Model building–within is the averaged bidimensional correlation coefficients for the four buildings within each route.
* $p < .05$. ** $p < .01$.

recruited for the two-part study had only 1 week in between initial learning and the Building Cued Recall task.

Route Membership Task. This behavioral task was designed to probe the structure of participants' representations of the buildings in Virtual Silcton. Participants were first refreshed on the spatial layout and buildings of Virtual Silcton by walking through each of the main routes one time, and one of the connecting routes, from beginning to end but not back. This was to ensure that better performance on this task was not entirely related to some participants not remembering which building was which. For the Route Membership Task, two images of Virtual Silcton buildings appeared on screen without names. Participants pressed one key on a keyboard to indicate that the buildings were from the same main route, and another key to indicate that the buildings were from different main routes. Pairs of buildings were presented randomly, with each possible pair appearing twice (once with Building A on the right, once with Building A on the left), yielding 64 total trials. Reaction time (RT) and accuracy were recorded. A special keyboard was used, which had only the J and F keys, to reduce error because of pressing the incorrect key. Which key was mapped to "same" and which mapped to "different" was counterbalanced between participants.

Procedure. The cognitive battery was collected in two sessions, each approximately one hour long. In Part 1, participants provided informed consent and were briefed on the purpose of the study—to study human navigation in a virtual environment. Participants then completed the following on a desktop computer, in the same order for all participants: the demographics questionnaire, the SBSOD, Virtual Silcton, and the SAQ. In Part 2, participants completed the WRAT-4, then the Building Cued Recall Task, one of the working memory tests, the refresher on Virtual Silcton, the other working memory test, and, finally, the Route Membership Task. The working memory tasks were counterbalanced across participants.

Some data were lost because of experimenter or computer error. This loss of data was random, distributed across participants, and did not account for more than 10% of the total sample for any given measure. Participants were not deleted from the sample if they were missing on any task, but rather included in all analyses for which we had data. Degrees of freedom for each test vary to reflect these lost cases.

Results

To divide the participants into groups, a two-step cluster analysis was conducted in SPSS, Version 21, with the number of clusters constrained to three, using each participant's between-route pointing and within-route pointing scores. Each participant's cluster membership was used to divide the participants into one of three groups.[1] Figure 2 provides a scatterplot showing the distribution of participants. Unless otherwise specified, follow-up contrasts were conducted when omnibus ANOVAs showed a significant effect of pointing group, and were assessed at a Bonferroni-corrected threshold of $p < .05$.

Working memory capacity.

Spatial working memory. The three groups had significantly different scores on the complex spatial working memory span task, $F(2, 71) = 4.32$, $p = .017$, $\omega^2 = .08$. This effect was driven by integrators ($M = 32.14$, $SD = 7.28$) and non-integrators ($M = 30.92$, $SD = 6.78$) scoring higher than the imprecise navigators ($M = 25.12$, $SD = 10.32$). To rule out the possibility that these results were driven by underlying differences in the pointing groups on verbal IQ, we ran an ANCOVA controlling for group differences in verbal IQ (measured by the WRAT-4) for native English speakers, $F(2, 52) = 3.59$, $p = .035$, $\omega^2 = .09$, and found that the groups remained significantly different.

Verbal working memory. The pattern of performance for the verbal working memory task was nearly identical to that of the spatial working memory task, with the pointing groups performing significantly differently overall, $F(2, 68) = 7.92$, $p = .001$, $\omega^2 = .16$. Integrators ($M = 62.05$, $SD = 8.54$) and non-integrators ($M = 60.82$, $SD = 10.70$) again scored higher than the imprecise navigators ($M = 47.31$, $SD = 18.69$). This effect was attenuated when verbal IQ score was included in an ANCOVA controlling for WRAT-4 among native English speakers, $F(2, 51) = 2.76$, $p = .073$, $\omega^2 = .05$.

Correlational analysis. In addition to the cluster-based analysis, we tested whether within-route and/or between-route pointing was predicted by working memory capacity. Spatial and verbal working memory were significantly correlated with each other, $r(70) = .57$, $p < .001$. Verbal and spatial working memory measures were each significantly correlated with within-route pointing (see Table 1), but neither was correlated with between-route pointing. The pattern was similar with partial correlations of one working memory measure controlling for the other. This pattern may suggest that domain-general working memory capacity distinguishes performance on within-route learning, rather than the differential contributions of one specific modality. But it is also possible that both types of working memory are required by different aspects of the task.

Building cued recall. Do imprecise navigators have lower long-term recall of the names of the buildings as well as lower working memory? Lower working memory capacity might lead to less verbal rehearsal of building names and/or less visuospatial rehearsal of images of buildings and/or to less ongoing review of the linkages between names and images. Results from the building naming task, taken at the beginning of Session 2, showed significant differences among the three pointing-groups, $F(2, 71) = 6.61$, $p = .002$, $\omega^2 = 0.13$. Integrators were able to name the most buildings ($M = 6.33$, $SD = 1.80$), followed by non-integrators ($M = 5.44$, $SD = 2.05$), followed by the imprecise navigators ($M = 4.06$, $SD = 1.78$). Because of the differences in recruiting methods, some participants had longer lengths of time between sessions than others. We thus ran a 2 × 3 ANOVA with recruiting method and pointing groups as between-subjects factors. Participants who had only 1 week between sessions ($M = 6.22$, $SD = 1.77$) significantly outperformed participants who had between 1 and 5 weeks ($M = 4.33$, $SD = 1.85$), $F(1, 68) = 27.42$, $p < .001$, $\omega^2 = 0.22$. However, the main effect of pointing groups was still significant, $F(2, 68) = 9.75$, $p < .001$, $\omega^2 = 0.15$, and there was no significant interaction, $F(2, 68) = 0.27$, $p = .76$, $\omega^2 = 0.00$. Verbal working memory was not correlated with the number of

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[1] The cluster analysis was generated in several ways (see Table 3 and The Overall Pattern: Analyses Across Data Sets section). Because group membership varies very little as a function of analysis method, all results are reported as the clusters generated using the two-step cluster analysis, constrained to three groups, conducted within each study separately.

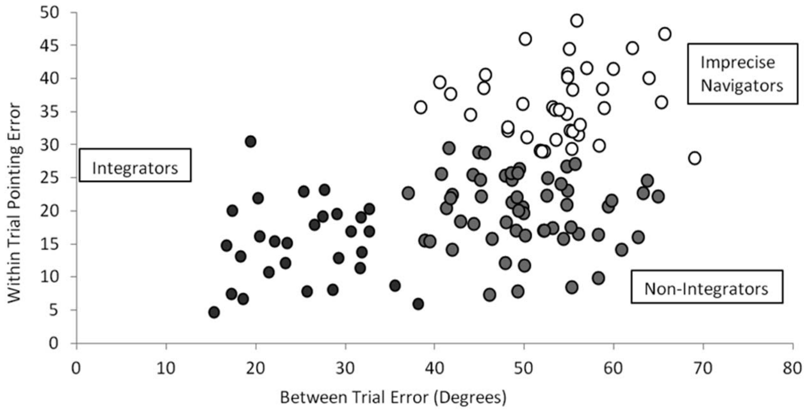

Figure 2. Scatterplot for between- and within-route pointing error, Study 1. The distribution of participant's pointing error for between- and within-route pointing trials shows the characteristic three-quadrant pattern found in Weisberg et al. (2014). Chance performance on both types of pointing judgments is 90°. Optimal performance is approximately 10° to 15°, as participants pointed to the front door of each building, which was sometimes obscured or not obvious.

buildings participants were able to name, $r(72) = .20$, $p = .10$, but spatial working memory was correlated, $r(75) = .24$, $p = .04$.

Route membership task.

Accuracy. The three groups varied on accuracy in the route membership task, $F(2, 71) = 11.70$, $p < .001$, $\omega^2 = .10$, although each group scored significantly greater than chance (50%; all $ps >$ .001). Follow-up contrasts revealed the integrators (M = 91.4%, $SD = 9.23$) significantly outperformed the non-integrators (M = 81.4%, $SD = 19.86$), $t(55) = 2.17$, $p = .035$, $d = 0.61$, who outperformed the imprecise navigators (M = 65.4%, $SD = 15.72$), $t(51) = 2.92$, $p = .005$, $d = 0.88$. Among native English speakers, these results remained significant controlling for WRAT-4, $F(2, 52) = 5.16$, $p = .009$, $\omega^2 = .12$. Performance did not differ on this task as a function of whether the trial was a within-route or between-route trial, $t(74) = 0.96$, $p = .34$.

RT. The pointing-groups also significantly differed on RT for the Route Membership Task, excluding incorrect trials, $F(2, 71) = 5.21$, $p = .008$, $\omega^2 = .10$. Integrators were the fastest (M = 1.86 s, SD = 0.64), followed by non-integrators (M = 2.21 s, $SD = 0.53$), followed by the imprecise navigators (M = 2.55 s, $SD = 0.90$). RT also significantly differed based on whether the correct answer for the trial was between-route or within-route, $t(73) = 2.77$, $p = .007$, because participants were faster to respond to within-route trials (M = 2.14 s, $SD = 0.73$) than between-route trials (M = 2.24 s, $SD = 0.75$).

Discussion

Previous research using the Virtual Silcton paradigm defined three groups (Weisberg et al., 2014). However, in that study, the two groups who performed poorly on the between-route pointing tasks (non-integrators and imprecise navigators) were indistinguishable from each other in terms of scores on mental rotation task, spatial orientation, and self-reported sense-of-direction measures, despite having markedly distinct scores on within-route pointing tasks. In Study 1, we found that imprecise navigators had worse accuracy on their within-route pointing judgments, and correspondingly low working memory capacity. They had significantly lower scores on both the spatial and verbal working memory tasks compared with the integrators and non-integrators, who did not differ from each other. Within-route pointing was significantly correlated with both working memory measures, whereas between-route pointing was not. Overall, this pattern of data suggests that imprecise navigators are not able to effectively learn the buildings' names, images, and/or name–image pairings, as suggested in particular by their poor performance on the route membership task, and implied by weaker performance on both working memory tasks; lacking such knowledge, they would certainly have difficulty in pointing to one building from another.

Interestingly, integrators and non-integrators did not differ on either domain of working memory. The fact that integrators did not have greater spatial or verbal working memory than non-integrators suggests that between-route learning relates less than within-route learning to storing and updating visuospatial configurations. Between-route pointing may require inferential or strategic capacities to support integration across routes, factors which were not directly assayed in Study 1.

We also found that integrators did not discard route information about the buildings in favor of a more global encoding as they built integrated representations. Instead, they maintained route information as well as or better than non-integrators, but integrated routes in a hierarchical fashion in which within-route information was maintained. This pattern of data suggests that non-integrators are indeed an intermediate group in navigation skills, building some route knowledge but not yet adept at establishing a hierarchical relation among routes. (These results are not likely to be related to integrators recalling more of the building names and images, because participants were refreshed on the routes prior to completing the route membership task.) An alternative interpretation of these data is that, instead of hierarchical representations, integrators built global and local representations separately, and drew on these representations differently for the pointing task, model-building task, and route membership task. The current findings could be related to the way in which the environment was explored (i.e., two routes were learned first, and connected by two separate routes). Future work should systematically explore the relationship between environmental structure and representational structure (as in Han & Becker, 2014).

These results shed light on the process of building cognitive maps, suggesting a two-step process in which routes are learned first and then related to each other. However, because the routes were learned first, then connected, this finding may be idiosyncratic to the particular paradigm. Accurate within-route judgments are possible if participants simply recall the sequence of locations encountered and a rough approximation of the turns. The working memory capacity necessary to build such a chain of name–image pairs and turns is necessary and may be sufficient for success on within-route pointing tasks. It is important to note that 10° to 15° is approximately ceiling performance for pointing judgments, and that most integrators and non-integrators are in or around this range. This is because small deviations in pointing to the buildings themselves, instead of precisely pointing to the front door, yield degrees of error in that range, despite participants pointing accurately at some part of the building. The connecting routes provide a path between segments of the two routes, but inferences must still be made about how the buildings along the two routes relate to each other overall. As a result, between-route judgments require much more difficult spatial inference.

Nevertheless, even imprecise navigators performed above chance for between-route judgments. The implied boundaries of the virtual environment may have been used by imprecise navigators (indeed, all navigators) to infer where the buildings were not. One way to perform inferences about the relation between routes, or about the routes and the global environment, is to relate each route to an outside frame of reference, that is, to use a place-based strategy. Perhaps the three groups also differ in the extent to which they use outside frames of reference. Do integrators use a more place-based strategy than non-integrators when given options in navigation, with imprecise navigators using such frames the least (that is, either with a preference for response-based strategy or with no discernible preference for place- or response-based strategy)? Alternatively, are some individuals better able to use a place-based approach, if they choose to use it? Assessing these issues of coding and preference for outside frames of reference was the purpose of Study 2.

Study 2: Navigation Strategy and Navigation Proficiency

Table 2 provides correlations among measures from the DSP and Virtual Silcton. Using a place-based approach involves coding location using common external frames of reference, which then allows for inferences about between-route spatial relations. There is a large and classic literature on place-based and response-based spatial learning (e.g., Munn, 1950; Restle, 1957; Tolman, Ritchie, & Kalish, 1946), which have been shown to depend on the hippocampus and the caudate, respectively (McDonald & White, 1994; Morris, Garrud, Rawlins, & O'Keefe, 1982; Packard & McGaugh, 1996). In humans, better navigators have larger (Maguire et al., 2000, 2006; Schinazi et al., 2013; Woollett & Maguire, 2011) or more active (Hartley, Maguire, Spiers, & Burgess, 2003) hippocampi and smaller or less active caudates. In line with these findings, Marchette, Bakker, and Shelton (2011) found that human participants' preference for a place-based strategy was positively correlated with the ratio of hippocampal to caudal activity during encoding. However, Marchette and colleagues also observed that using a place-based strategy was uncorrelated with success in finding goals in their virtual environment maze learning environment, given that success was possible with either a place or a response approach. No research has yet examined the relation between place-based learning and performance in the route integration paradigm. Do integrators prefer a place-based strategy? Alternatively or in addition, are they more successful in using a place strategy when they opt for it?

The dual solution paradigm (DSP) uses a very different virtual environment from Virtual Silcton and assesses use of place- and response-based way-finding strategies. It has revealed wide individual differences in following a familiar route versus taking a novel shortcut to find a goal in a situation in which either strategy can work well (e.g., Marchette et al., 2011). Although they found no relationship between navigation strategy and success in finding goals, Marchette et al. (2011) found involvement of the hippocampus in place-based strategy use. Given that the hippocampus is also involved in route integration success (Schinazi et al., 2013), it seems possible that using a place strategy is related to route integration.

However, because the DSP affords multiple strategies to successful navigation, although success in route integration probably requires a strong sense of direction, the relation might not be straightforward. That is, integrators might choose to use a response strategy, given that it works and they have strong route representations, and that the task does not require finding shortcuts. However, when people do choose to look for shortcuts, integrators, but not the other pointing groups, should be better able to find such new routes, if integration is based on use of an allocentric framework. In Study 2, we sought to determine how these two paradigms tapping individual differences in way-finding relate to each other, and what the relation tells us about how integrators succeed in relating separated routes.

Method

Participants. Seventy-six participants were recruited to participate in a two-part study in exchange for class credit or $20 cash, with the same aim as Study 1 to aim for approximately 25 participants per group. Six participants had to be dropped because they either did not return for Part 2 or data was lost because of experimenter error. The resulting sample consisted of 70 college undergraduates (35 female). Of those, 61 were native English speakers. Seven participants were Asian, 15 were Black, 38 were White non-Hispanic, eight were Hispanic, and two did not report their ethnicity.

Measures.

Part 1. As in Study 1, we gathered demographic information, and administered the SBSOD and the SAQ. We counterbalanced the DSP (Marchette et al., 2011) and Virtual Silcton across Parts 1 and 2 such that half the participants took the DSP in Part 1 and Virtual Silcton in Part 2, and vice versa for the other half of participants. The DSP measures the extent to which an individual prefers a response-based strategy or a place-based strategy. This paradigm was adapted slightly from the version used by Marchette and colleagues (2011). Participants first learned the position of 12 objects around a maze-like environment by watching a video of one route through the maze on a desktop computer (see Figure 3 for an aerial view of the route). Images of the 12 objects were shown to participants and named before the video was shown, so

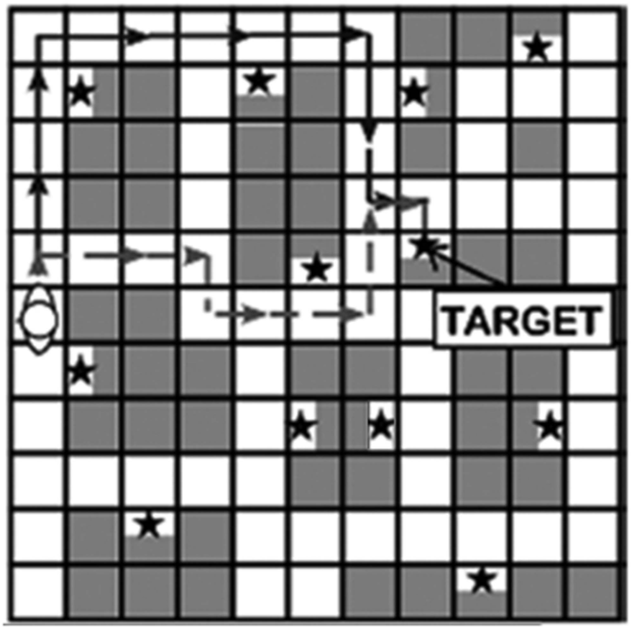

Figure 3. Aerial view of the dual solution paradigm with shortcut and familiar route solutions. The solid line indicates the familiar (learned) route, whereas the dashed line indicates a novel shortcut the participant could have taken to find the target. Stars indicate the positions of the 12 objects. Adapted from Marchette et al. (2011).

participants knew how to identify them during encoding. In the DSP environment, distal mountains were four different colors, with approximately a quarter of the horizon taken up by each color. These distal cues could be used by participants, but were not pointed out or interacted with in any way. Unlike Virtual Silcton, participants did not use the mouse and keyboard to learn the environment in the DSP. Encoding consisted of "learn trials," wherein participants watched this video while memorizing the positions of the objects. Learn trials were interspersed with "match trials," wherein participants watched videos in a similar environment in which red or blue floating balls appeared throughout the route. At the end of match trials, participants had to determine whether the color of the first ball matched the color of the last ball and press the "M" key on the keyboard to indicate a match, and the "Z" key to indicate a mismatch. The purpose of the match trials was to keep participants engaged in the learning phase, as there was no required response during learn trials.

After encoding, participants completed 24 retrieval trials. In a retrieval trial, participants were placed nearby one of the 12 objects, rotated automatically to view the surrounding area, and then prompted to find another of the objects with text that displayed the name of the object. Participants were given 30 s to complete each retrieval trial, after which the trial was terminated regardless of whether the participant found the goal or not. If the participant found the goal, the trial was terminated immediately. For 16 of these trials, a novel shortcut was available (shortcut-available trials), which was shorter than the familiar route shown in the video during encoding. The other eight trials were catch trials, for which the familiar route was either the same length as an alternate path or the familiar route was the shortest available path to the goal. These trials ensured that the participant did not simply wander the environment to find a short path, but had to consider the spatial arrangement of objects to determine if a shortcut was available on that particular trial. For the 16 shortcut available trials, if a participant traveled along a higher proportion of novel shortcut path segments than familiar route segments, that trial was classified as a "shortcut" trial, or a "familiar route" trial for the opposite pattern (more familiar route segments than shortcut segments). If a participant did not travel on either a shortcut path or the familiar path, or traveled on those paths an equal amount, the trial was classified as neither. The proportion of these 16 trials for which participants found the goal using a shortcut divided by the total number of trials for which the participant found the goal using a shortcut or a familiar route yielded each participant's "place/response index." The higher this ratio was, the more that participant used a place strategy in encoding and retrieving the objects around the maze. Participants were scored both on the percentage of trials for which a shortcut is taken and the success in reaching the goal (number of shortcut-available trials found), regardless of the route taken.

In Study 2, we administered the building naming task immediately after the model-building task in the same session as Virtual Silcton. In addition, we administered the MRT (Vandenberg & Kuse, 1978; adapted by Peters et al., 1995). The MRT consists of items made up of one target image composed of a number of individual cubes. Participants must choose the two (out of four) objects that correspond to the target after being rigidly rotated. Scoring correcting for guessing was applied such that participants received 2 points for each correct response, but lost 2 points for an incorrect response. No points were awarded or rescinded for omissions. The MRT consists of two parts of 10 items each, with 3 min allotted for each part of the test.

Part 2. As in Study 1, we administered the WRAT-4. Participants then completed whichever navigation measure (Virtual Silcton or the DSP) they did not complete in Part 1.

Procedure. Parts 1 and 2 were identical for all participants, with the exception of whether DSP was taken in Part 1 or Part 2. The procedure for Part 1 was identical to that of Part 1 of Study 1 except that the MRT was administered at the end. For Part 2, participants first completed the WRAT-4, then completed the navigation measure.

Results

Preliminary analyses. The same method was adopted in clustering the participants into groups on between- and within-route pointing judgments from the Virtual Silcton paradigm as was used in Weisberg and colleagues (2014) and in Study 1. Figure 4 gives the distribution of participant's between- and within-route pointing scores.

We replicated the results for the building naming task from Study 1, even when it was administered directly after the other Virtual Silcton measures. Integrators remembered the most building names ($M = 7.54$, $SD = 0.93$), non-integrators remembered slightly fewer ($M = 7.00$, $SD = 1.22$), and imprecise navigators remembered the fewest, ($M = 6.14$, $SD = 1.32$), $F(2, 66) = 7.56$, $p = .001$, $\omega^2 = 0.16$.

Navigation proficiency. Both Virtual Silcton and the DSP contain measures of navigation proficiency, that is, how well

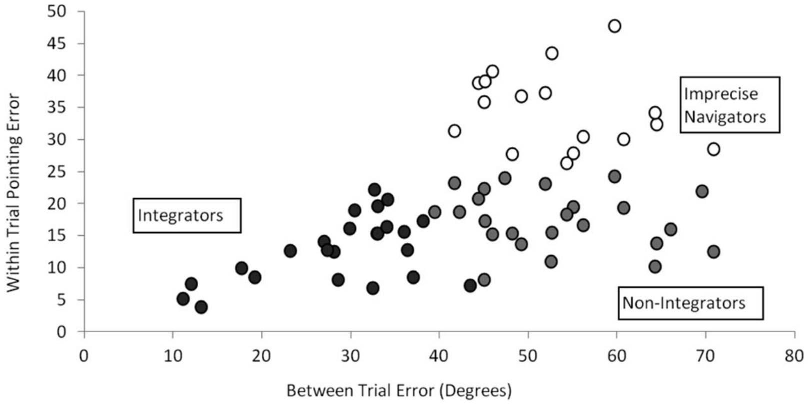

Figure 4. Scatterplot for between- and within-route pointing error, Study 2. The distribution of participants' pointing errors for between- and within-route pointing trials shows the characteristic three-quadrant pattern found in Weisberg et al. (2014). Chance performance on both types of pointing judgments is 90°.

participants could learn the layout of objects or buildings around a space. In other words, how successful were participants on the two navigation tasks? To assess whether the pointing groups from Virtual Silcton had different levels of navigation proficiency on the DSP, we conducted an ANOVA with pointing-group membership as a between-subjects factor and the number of shortcut goals found successfully (regardless of strategy used) as the dependent variable. For all subjects, we found a significant effect of pointing-group membership on navigation success for shortcut-available trials, $F(2, 66) = 4.11$, $p = .02$, $\omega^2 = .08$. For native-English-speaking subjects, controlling for verbal IQ as measured by the WRAT-4 using an ANCOVA, this effect remained significant, $F(2, 57) = 3.79$, $p = .03$, $\omega^2 = .08$. Using Bonferroni's correction for multiple comparisons, follow-up pairwise contrasts revealed that this effect was driven by a significant difference between the integrators, who found more goals in the DSP, and the imprecise navigators, who found fewer goals, $t(43) = 2.81$, $p = .007$, $d = 0.86$. The pairwise contrasts involving the non-integrators were not significant, but the pattern of means suggested integrators ($M = 9.38$, $SD = 3.60$) and non-integrators ($M = 9.00$, $SD = 3.67$) outperformed the imprecise navigators ($M = 6.67$, $SD = 2.74$).

Navigation strategy. There was no significant difference between the pointing-group clusters on the place-response index, $F(2, 66) = 0.13$, $p = .88$, $\omega^2 = .00$. Along the same lines, previous research using the DSP has found no relationship between navigation strategy and the number of shortcut goals found (Furman, Clements-Stephens, Marchette, & Shelton, 2014; Marchette et al., 2011); we analyzed data using correlation and median-split (on place-response index) methods to replicate both findings here, $r(71) = -.01$, $p = .95$, $t(69) = 0.38$, $p = .71$, $d = 0.09$.

Strategy and proficiency. Participants in the DSP may differ in their ability to use their preferred strategies. As one way to probe this issue, we examined relations between the place-response index and navigation success on the DSP, separately for the three Virtual Silcton groups. Figure 5 shows the three scatterplots. Integrators found more goals on shortcut trials if they used a place-based strategy, $r(24) = .46$, $p = .023$. Non-integrators found approximately equal numbers of goals on shortcut trials whether they used place- or response-based strategies, $r(24) = -.26$, $p = .22$. The imprecise navigators found somewhat more goals on shortcut trials if they used a response-based strategy, $r(21) = -.35$, $p = .13$. Integrators and non-integrators had significantly different correlations from each other (Fisher's r-to-z transformation), $z = 2.47$, $p = .014$, as did the integrators and the imprecise navigators, $z = 2.69$, $p = .007$. For the non-integrators, a quadratic curve improved the fit a little, $\Delta R^2 = .107$, but not significantly, $p = .13$.

We also tested our prediction that, among place-preferring participants, only integrators would excel at finding goals on the shortcut trials. We divided the participants into three approximately equal groups, based on their place-response index (24 place-preferring, 23 no-preference, and 24 response-preferring).

Table 2
Dual Solution Paradigm Performance and Pointing Correlations

Measure	1	2	3	4	5	6	*M*	*SD*
1. Within-route pointing	—	—	—	—	—	—	20.98	10.43
2. Between-route pointing	$.50^{**}$	—	—	—	—	—	44.78	14.49
3. SAT–Shortcut	$-.34^{**}$	$-.31^{**}$	—	—	—	—	3.51	2.56
4. SAT–Route	−.13	.03	$-.32^{**}$	—	—	—	3.70	2.69
5. SAT–Total	$-.43^{**}$	$-.29^{*}$	$.66^{**}$	$.46^{**}$	—	—	8.42	3.54
6. Model building–within	−.16	−.03	.01	.05	.02	—	.66	.18
5. Model building–total	$-.49^{**}$	$-.57^{**}$	.19	.01	.20	.11	.49	.27

Note. Pointing errors are for Virtual Silcton. SAT = shortcut available trials (on the dual solution paradigm).
$^{*} p < .05$. $^{**} p < .01$.

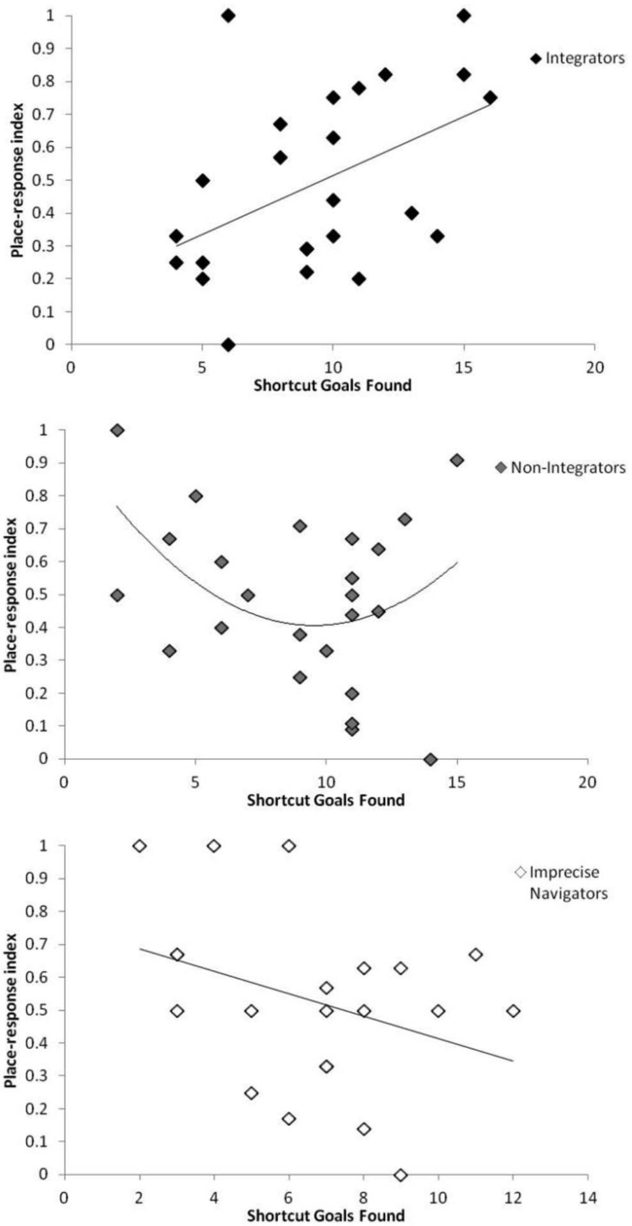

Figure 5. Relations between place-response index and goals found on shortcut available trials by pointing group. The integrators and imprecise navigators had significantly different relations between the number of goals found on shortcut-available trials and the extent to which they preferred a place-based strategy. The non-integrators, overall, had a negative linear relation, but a U-shaped curve fit the data marginally better than a linear trend.

We then ran an ANOVA across the pointing groups for the participants who preferred place-learning. The three place-preferring pointing groups found a significantly different number of goals, $F(2, 19) = 5.02$, $p = .02$, $\omega^2 = 0.27$. Integrators found the most goals ($M = 11.6$, $SD = 1.27$), followed by the non-integrators ($M = 8.9$, $SD = 1.66$) and the imprecise navigators ($M = 4.8$, $SD = 1.35$). Participants in the middle third of the place-response index (i.e., those with no preference for response or place learning) did not perform better or worse as a function of pointing group, $F(2, 20) = 0.43$, $p = .66$, $\omega^2 = 0.00$. Nor were there differences for participants who preferred response-learning, $F(2, 21) = 2.01$, $p = .16$, $\omega^2 = 0.08$. Figure 6 exhibits the pattern of success across place-response index and pointing groups.

Discussion

In Study 2, we investigated the role of navigation strategy preference, as measured by the DSP, in success on the route integration paradigm. We found that integrators were indeed better spatial learners, in that they found more goals on the DSP. Although they were not more likely to use a place-based strategy in finding the goals, integrators did find more goals when they were using a place-based strategy (i.e., taking more shortcuts than familiar-route paths), suggesting that they were proficient at using place learning. Indeed, they excelled among people who chose a place-based strategy. This pattern raises the question of why integrators sometimes use a response-based strategy. Perhaps some integrators think it is safer and more conservative, or they thought the experiment required it, even though the instructions to navigate as efficiently and accurately as possible were intentionally vague.

The imprecise navigators displayed a significantly different pattern from the integrators, tending to find more goals using a response-based strategy (see Figure 5). The slight negative correlation between success on the DSP and place-response index for the imprecise navigators, combined with the significantly different positive correlation for the integrators, suggest that people are best off choosing the strategy that fits their navigation strategy proclivity. Indeed, for those who are unsure of their navigational competence, following a familiar route is a safe, relatively error-proof strategy.

The non-integrators, although more successful than the imprecise navigators, comprised a more heterogeneous distribution—

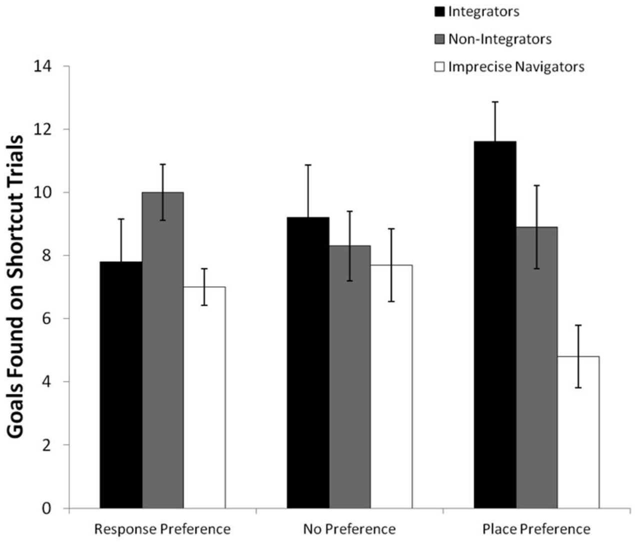

Figure 6. Success on the DSP varied by pointing group and place-response index. Integrators were the only group who could succeed on the DSP if they preferred a place strategy. Error bars represent ±1 *SEM*. DSP = dual solution paradigm.

participants preferring either strategy could be successful. The non-integrators, as the middle panel of Figure 5 suggests, displayed an odd relationship between success on the DSP and strategy preference. One possibility is that the non-integrators are a heterogeneous group, some of whom followed a trend similar to the integrators (on the right half of the graph), whereas the other half showed a trend similar to the imprecise navigators. Another possibility is that the within-route learning which non-integrators exhibit is actually evidence of place-learning (at least for some non-integrators), allowing them to accurately point between buildings that are along the same route. This nuanced relationship between navigation success and strategy merits further exploration.

These results make clear that navigators differ in both strategy preference and proficiency, with the two constructs being importantly distinguishable. Recent work with functional neuroimaging has provided evidence that both place and response systems are engaged during encoding and retrieval (Furman et al., 2014). However, different strategies work better or worse given different kinds of underlying representations. Strong navigators use place information from the hippocampus more effectively to find the goals. Weaker navigators may try to find novel shortcuts, but find it difficult, and may be better off relying on the caudal representation of the familiar route. Another possibility, which cannot be ruled out and merits further investigation, is that distinct mechanisms support accurate route integration in Virtual Silcton and accurate place-based navigation in the DSP (e.g., path integration vs. an allocentric framework).

Study 3: The Role of Motivation

One possible explanation for the poorer performance of imprecise navigators in learning routes and between-route relations could be that they are unmotivated to complete most of the experimental tasks. Although participants receive course credit or $10 cash in exchange for participation in the study, there is no incentive to attend to the tasks or to aim to do well. To address this possibility, we devised a manipulation wherein participants were told, before the study began, that if they perform within the top half of all participants, they would be entered in a raffle to receive a $100 prize. The logic is that if we find substantially fewer imprecise navigators, some participants in prior studies were likely not motivated to perform as accurately as they could. Indeed, we might also find more integrators, if some non-integrators in prior studies could have inferred connections between the routes if more motivated.

Method

Participants. Forty-nine participants were recruited to participate in a one-part study in exchange for class credit, with the aim to collect either approximately 50 subjects (to match the number of participants collected in Weisberg et al., 2014) or to terminate at the end of the academic semester. Three participants had to be dropped because data was lost because of experimenter error. The resulting sample consisted of 46 college undergraduates (28 female, one omitted). Of those, 43 were native English speakers (one omitted). Eight participants were Asian, three were Black, 30 were White non-Hispanic, two were Hispanic, one was Native American or Alaskan, and two did not report their ethnicity.

Measures. As in Studies 1 and 2, in addition to Virtual Silcton, we gathered demographic information, and administered the WRAT-4, the SBSOD, and the SAQ. We also asked a one-item question as a manipulation check. Participants were asked to indicate how strongly they agreed with the following statement, on a scale of 1 (*I tried no harder than I would have for a study with no bonus prize*) to 7 (*I tried much harder than if there was no prize based on performance*): “How motivating did you find the raffle?”

Procedure. Participants first completed the WRAT-4, demographics, and the SBSOD questionnaires. Before learning the routes in Virtual Silcton, participants were instructed that they would have the opportunity to win an extra prize if they perform well enough: “The top 25 participants out of 50 will be entered in a raffle to win an extra $100. Compared with previous semesters, performance has been quite low, so your odds of making the top 50% are really good.” Then, as in Studies 1 and 2, participants learned the four Virtual Silcton routes, completed the onsite pointing and model-building tasks, filled out the SAQ, and, finally, answered the motivation question. Participants were debriefed and informed that, in fact, all participants would be entered in the raffle and that two $100 prizes would be awarded (so the odds were the same as advertised).

Results

Preliminary analyses. The same method was adopted in clustering the participants into groups on between- and within-route pointing judgments from the Virtual Silcton paradigm, as was used in Weisberg and colleagues (2014) and in Studies 1 and 2. Figure 7 gives the distribution of participant’s between- and within-route pointing scores (compared with the distributions from those studies).

Manipulation check. We first wanted to determine how well our manipulation worked by looking at our one-item manipulation question. Participants were moderately motivated to complete the Virtual Silcton measures ($M = 3.39$, $SD = 1.82$), encompassing the full range (1 to 7). Importantly, response to the motivation item did not correlate with between- or within-pointing, model-building, SBSOD, or WRAT-4 (all $ps < .08$), nor did it differ by pointing group, $F(2, 43) = 0.20$, $p = .82$, $\omega^2 = 0.00$, or gender, $t(43) = 0.60$, $p = .55$, $d = .19$ (males, $M = 3.24$, were numerically less motivated than females, $M = 3.57$). These results suggest that our manipulation had a modest effect, at least judging by self-report, but that this effect was not differential across participants. We also found that the time spent exploring the routes did not differ between integrators ($M = 911$ s, $SD = 122$), non-integrators ($M = 976$ s, $SD = 164$), and imprecise navigators ($M = 988$ s, $SD = 177$), nor did time spent in the environments correlate with the self-reported motivation, $r(46) = -.16$, $p = .29$.

Comparison with Studies 1 and 2. We next wanted to determine whether motivating participants to perform better on the Virtual Silcton tasks would change the pattern of data. We tested this in several ways. First, we tested whether the pattern of participants in clusters differed substantially between Studies 1 and 2 (combined), compared with Study 3, and found that it did not, $\chi^2(2) = 4.88$, $p = .09$. We also tested this question using the clusters generated across all studies, and found that the pattern of participant allocation across the three clusters did not differ using these divisions, $\chi^2(2) = 0.92$, $p = .63$. Second, we wanted to see

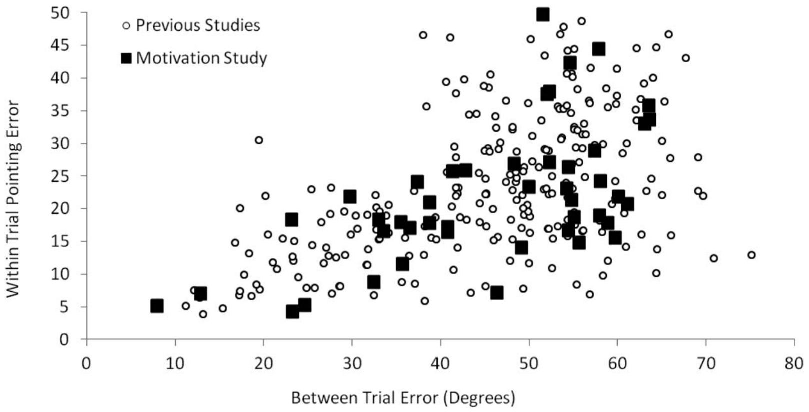

Figure 7. Scatterplot of participants from all four studies. The distribution of participants on between- and within-pointing from the motivation study (Study 3, in black squares) shows they do not differ from participants in previously published studies (Weisberg et al., 2014) and Studies 1 and 2 from the present work (white circles).

whether participants in each cluster differed from their counterparts in Studies 1 and 2 (i.e., were imprecise navigators in Study 3 more accurate on within-route pointing than imprecise navigators in Studies 1 and 2, despite being classified similarly)? Omitting one outlier, who performed unusually poorly on within-route pointing (77.27°), 4.5 standard deviations above the mean of all three studies ($M = 23.66°$, $SD = 11.87$), imprecise navigators in Study 3 did not differ in accuracy compared with their counterparts in Studies 1 and 2 for within-route pointing ($M_{\text{Study3}} = 39.29$, $SD = 5.78$; $M_{\text{Study1 + 2}} = 36.49$, $SD = 6.44$), $t(44) = 1.14$, $p = .26$, $d = .74$, and for between-route pointing ($M_{\text{Study3}} = 57.31$, $SD = 5.42$; $M_{\text{Study1 + 2}} = 53.50$, $SD = 7.50$), $t(44) = 1.36$, $p = .18$, $d = 0.54$. If anything, Study 3 participants were worse—a pattern that extended across all three groups.

Discussion

In Study 3, we manipulated motivation by providing a monetary incentive for good performance, but found that participants did not significantly improve. Additional work should investigate other potential factors, which the motivation manipulation may not have affected. For instance, participants may not have believed they could attain performance in the top half and may need to boost their self-efficacy. Additionally, manipulating instructions has been shown to affect how participants approach navigation tasks, and could yield more participants to attend to between-route integration (e.g., Wolbers & Büchel, 2005; Wolbers, Weiller, & Büchel, 2004). These effects should be investigated directly in future research. Still, these findings provide support for the claims of Study 1 that within-route performance in particular is related to working memory capacity and not general motivational differences.

The Overall Pattern: Analyses Across Data Sets

These three studies, along with the data from the previous study on Virtual Silcton (Weisberg et al., 2014), provide information on close to 300 people performing the Virtual Silcton paradigm. Several important questions can be explored in a powerful way using the combined data set, including analyzing the validity of the Virtual Silcton cluster-group approach, and exploring individual difference measures. To address the first question, we first conducted a taxometric analysis to determine whether a categorical or continuous approach better captures the structure of the Virtual Silcton pointing tasks. We then conducted the cluster analyses again, both across and within data sets, to determine the stability of the groups. Finally, we looked more closely at the model-building task to see whether it conceptually replicates the results from the pointing task.

For the second question, across the studies, we chose individual difference measures to explore the extent to which self-reported navigation ability, and objectively measured small-scale spatial ability, relate to performance on the Virtual Silcton paradigm. We included as many such measures as we could in our studies, while keeping the total time reasonable (i.e., less than one hour per session). We discuss our reasons for including specific measures in the Discussion section of this study, but they were self-report measures of sense of direction (SBSOD), verbal ability (Philadelphia Verbal Ability Scale; PVAS), small-scale spatial ability (Philadelphia Spatial Ability Scale; PSAS), and spatial anxiety (SAQ), a measure of verbal intelligence (WRAT-4), and a measure of small-scale spatial ability (MRT). For all of these, we looked at sex differences and at differences among the three pointing groups.

Validity Analyses

Taxometric analyses. We began with a taxometric analysis (Meehl & Yonce, 1994, 1996) to determine whether the data from the within- and between-route pointing judgments would be better described with a categorical approach (i.e., group-based), as in Weisberg et al. (2014), or a dimensional approach (i.e., continuous). Taxometry assesses which format data fit better, to determine which analyses are appropriate. Taxometry has previously only been used to determine whether data better fit a two-group or dimensional structure. Because we have strong evidence for a three-group structure, we modified traditional taxometric analyses by taking a sequential approach. For both steps in the sequence, we analyzed the data with categories created by SPSS' two-step cluster analysis (across all data sets, instead of using individual study clusters), and without (see Ruscio, 2010 for details). In the first step, we determined whether the overall pattern of between- and within-pointing judgments better fit a two-group or dimensional structure. In the two-step cluster analysis method, constraining the number of clusters to two results in a split between integrators and the other two groups, so we used integrator or other as our grouping variable. Then, we removed the integrators, and conducted the taxometric analysis a second time, to determine whether the remaining data fit a categorical or dimensional structure. In addition to conducting the analysis without a grouping variable, we used two groupings—one grouping divided participants into non-integrators and imprecise navigators; the other used groupings generated from SPSS' two-step cluster analysis constrained to two groups, conducted on the data set without integrators. This latter grouping resulted in a division between lower and higher performing participants on between-pointing, instead of within-pointing. Providing grouping variables allows the taxometric analyses to determine whether that particular two-group structure fits the data better than a dimensional structure. To the best of our knowledge, this sequential approach has not been conducted before, although there are no known faults to the logic (J. Ruscio, personal communication, April 30, 2015).

Using a script for the R statistical program (Ruscio, 2010), we ran a total of five taxometric procedures on data from all 294 participants who have completed the Virtual Silcton pointing task. The comparison curve fit index (CCFI) provides a metric for how closely the data adhere to a group structure (CCFI = 1) or a dimensional structure (CCFI = 0). CCFI was obtained for the mean above minus below a cut (MAMBAC) procedure and the L-Mode procedure. Results are presented in Table 3. The first two analyses provide evidence that the pointing tasks yield a categorical data structure for a two-group structure (between integrators and the other two groups, and between the other two groups). The final three analyses provide evidence that the remaining participants (omitting integrators) better fit a two-group structure. In general, the MAMBAC was more likely to provide support for a two-group structure than the L-Mode, which provided a CCFI in the ambiguous range between .40 and .60. Results are also more definitive when a group structure is provided for both sets of analyses, than when no group structure was provided. Overall, the taxometric analyses bolster the theoretical and visual assessment of the three-group structure.

Cluster analyses. Building on evidence that the pointing data are likely to be structured categorically, we wanted to see how stable the three-cluster structure is. We thus conducted a cluster analysis within each study, and across all four studies (the present three studies and the study previously reported in Weisberg et al., 2014), using several methods. We confined our analyses to three groups because these groups show differences on the other tasks (e.g., working memory, SBSOD), and because, visually, three clusters fit the pattern of between- and within-pointing. We conducted analyses using the k-means method and two-step cluster analysis (in SPSS Version 21), and found that group membership varied little across studies and across methods (see Table 4). Although lines were blurred for within-studies compared with across-studies clusters, the boundaries of the clusters were remarkably stable. For individual differences tests, we use the two-step clusters across all four studies.

We also conducted the pointing clustering to examine the issue of seen versus unseen trials. Seen trials were defined as pointing trials for which the buildings were mutually intervisible. This occurred for 14 of 24 within-route trials and 0 of 32 between-route trials. We looked at whether participants differed on seen-within and unseen-within trials as a function of pointing cluster. Integrators and non-integrators performed approximately equally well on both kinds of judgments. Thus, the present clusterings were apparently not driven by seen (or unseen) trials alone. However, the issue of intervisibility (as well as interbuilding distance and adjacency) needs further examination in richer environments with fuller and balanced crossing of these variables.

Model-building task. Results from the model-building task corroborate the division of groups using the pointing task. We conducted the bidimensional regression analysis using all eight buildings (model-building total; MB-total), and separately for the four buildings within each route (MB-within). To determine if model-building exhibited a similar pattern as the pointing task, we ran a 2 × 3 ANOVA with bidimensional regression type (MB-total or MB-within) as a within-subject factor, and pointing cluster as a between-subjects factor. We found an MB-Score × Group interaction (see Figure 8), $F(2, 288) = 13.00$, $p < .001$, such that integrators performed equally well on MB-within and MB-total ($M_{\text{within}} = .74$, $SD = .18$; $M_{\text{total}} = .69$, $SD = .25$), $t(87) = 1.55$, $p = .12$, whereas non-integrators performed significantly better on within-route compared with between-route model-building ($M_{\text{within}} = .64$, $SD = .19$; $M_{\text{total}} = .41$, $SD = .22$), $t(119) = 9.66$, $p < .001$.

Table 3
Results of Taxometric Analyses

Data	MAMBAC	L-Mode	Average	*n*
Integrators and others (with clusters)	.733	.649	.691	294
Integrators and others (no grouping variable)	.698	.346	.522	294
Non-integrators and imprecise navigators (with three-group clusters)	.749	.469	.609	206
Non-integrators and imprecise navigators (with two-group clusters)	.716	.411	.563	206
Non-integrators and imprecise navigators (no grouping variable)	.681	.399	.545	206

Note. Taxometric goodness-of-fit measures indicate categorical structure between integrators and the other groups, and between non-integrators and imprecise navigators. Providing cluster membership makes the categorical structure stronger, and MAMBAC more strongly suggests categories than L-Mode. MAMBAC = mean above minus below a cut.

Table 4
Numbers of Participants per Cluster Resulting From Different Clustering Analyses

	Pointing groups *ns*		
Clustering method	Integrators	Non-integrators	Imprecise
k-means			
Within studies	87	130	77
Across studies	84	131	79
Two-step			
Within studies	85	121	88
Across studies	75	130	89

Note. Various clustering analyses resulted in very similar numbers and patterns of participants across the three categories.

Individual Differences

Such a large sample allows us to test various individual difference factors. The right panel of Table 5 displays the significance of the statistical tests on these measures by pointing group. All p values reported in the remaining Results sections are evaluated at the Bonferroni-corrected level (i.e., $\alpha = .016$), but reported uncorrected.

Sex differences. Men were slightly, but not significantly, more likely to be integrators (36% of all men compared with 18% of women; Fisher's exact test, $p = .19$), significantly less likely to be imprecise navigators (18% of men compared with 39% of women; Fisher's exact test, $p < .001$), and equally likely to be non-integrators (46% of men compared with 43% of women; Fisher's exact test, $p = .32$). Men were significantly more accurate than women on within-pointing, $t(289) = 4.61$, $p < .001$, $d = 0.54$, and between-pointing, $t(289) = 3.51$, $p = .001$, $d = 0.41$, and the model-building task, $t(289) = 2.26$, $p = .03$, $d = 0.27$. On other measures, men self-reported better sense of direction on the SBSOD, $t(289) = 2.89$, $p = .005$, $d = 0.34$, and performed better on the WRAT-4, $t(186) = 3.02$, $p = .003$, $d = 0.44$, but not the MRT, $t(111) = 1.31$, $p = .19$, $d = 0.25$. The better performance of men on the WRAT-4 is not usually found, however, and suggests differential sampling of men and women. Controlling for WRAT-4 eliminates the sex difference on SBSOD and model-building, but not on either pointing measure. Differences are reduced in size ($d_{\text{SBSOD}} = 0.29$, $d_{\text{model-building}} = 0.23$, $d_{\text{between-pointing}} = 0.56$, $d_{\text{within-pointing}} = 0.50$).

SBSOD. Research shows that variance in navigation ability is related to self-reported sense of direction (Hegarty et al., 2002; Weisberg et al., 2014) and anxiety (Lawton, 1994). Previously, we showed that the SBSOD distinguished integrators from the other two groups, but did not distinguish non-integrators from imprecise navigators. Here, we wanted to see whether those findings replicated, and whether there were meaningful differences between the SBSOD and another major navigation questionnaire. The SBSOD correlated moderately but significantly with both within-pointing, $r(290) = -.29$, $p < .001$, and between-pointing, $r(290) = -0.32$, $p = <.001$. Pointing groups differed on the SBSOD such that integrators ($M = 4.80$, $SD = 0.96$) rated themselves more highly than non-integrators ($M = 4.34$, $SD = 0.88$), $t(201) = 3.47$, $p = .001$, $d = 0.51$, who rated themselves more highly than imprecise navigators ($M = 3.99$, $SD = 1.01$), $t(213) = 2.70$, $p = .008$, $d = 0.38$.

SAQ. Similar to the SBSOD, integrators scored significantly lower in spatial anxiety (M = 3.37, $SD = 1.03$) compared with the non-integrators ($M = 3.87$, $SD = 1.00$), $t(126) = 2.71$, $p = .008$, $d = 0.50$, and the imprecise navigators ($M = 3.94$, $SD = 1.08$), $t(110) = 2.87$, $p < .001$, $d = 0.54$, but these two groups were not significantly different from each other, $t(136) = 0.44$, $p = .66$, $d = 0.07$. The SAQ and SBSOD were highly correlated $r(190) = -.434$, $p < .001$, suggesting they tap similar aspects of self-reported navigation behavior. But the potential difference on these questionnaires for the non-integrators may be meaningful, and is worth future investigation.

PSAS and PVAS. The SBSOD and SAQ tap self-reported large-scale navigation ability, but we also wanted to see whether good navigation ability correlated with self-reported small-scale spatial ability (PSAS) and with self-reported verbal ability (PVAS). We included these measures in Weisberg et al. (2014), but left them out of the current studies because of time constraints, and because we had more objective measures of verbal ability (WRAT-4). Table 5 and Weisberg et al. (2014) provide these results.

MRT. Previous research has shown differences between large- and small-scale spatial abilities (e.g., Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006), so we included the MRT to examine this issue further. We predicted a modest correlation between MRT and Virtual Silcton in general, but were unsure how the measure would differ by pointing cluster. We also wanted to include the MRT as a way to replace the PSAS with a test of actual, instead of self-reported, ability. Integrators ($M = 35.94$, $SD = 17.33$) did not do significantly better than non-integrators ($M = 30.82$, $SD = 21.91$), $t(78) = 1.14$, $p = .26$, $d = 0.26$. Both integrators, $t(67) = 4.10$, $p < .001$, $d = 1.00$, and non-integrators, $t(75) = 2.68$, $p = .009$, $d = 0.63$, outperformed the imprecise navigators ($M = 18.06$, $SD = 18.91$).

WRAT-4. Finally, we wanted to rule out the possibility that general intelligence could explain the differences between the three groups. To this end, we administered an objective test that correlates highly with verbal intelligence—the WRAT-4. We

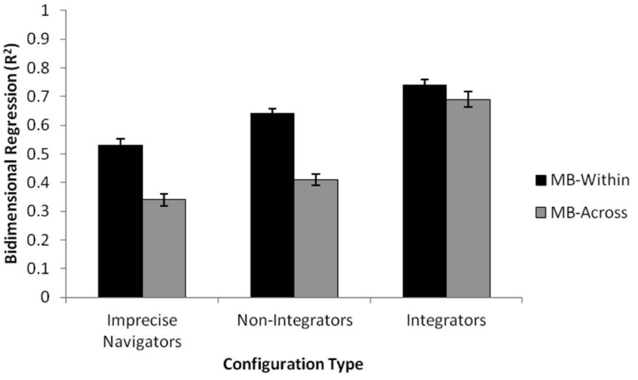

Figure 8. Model-building (MB) varies across the three groups. Integrators performed as well on overall model-building as for routes considered separately. Non-integrators and imprecise navigators performed significantly better on building within-route configurations than overall. A perfect score on the model-building task would be $R^2 = 1.0$. Error bars represent ±1 *SEM*.

Table 5
Means (and Standard Deviations) and Statistical Tests for Each of the Three Pointing Groups for Previous Study and Current Studies

		Pointing groups			Statistical tests			
Measures	Studies	Integrators (I)	Non-integrators (N)	Imprecise (C)	Omnibus	I vs. N	I vs. C	N vs. C
Virtual Silcton								
RMT	1	58.48 (5.90)	52.08 (12.71)	41.82 (10.06)	***		*	*
Model-building total	0–3	.69 (.25)	.41 (.22)	.35 (.19)	***	*	*	
Model-building within	0–3	.74 (.18)	.64 (.19)	.53 (.20)	***	*	*	*
Working memory								
Symmetry span	1	32.14 (7.28)	30.92 (6.77)	25.12 (10.33)	*		*	*
Operation span	1	62.05 (8.54)	60.82 (10.70)	47.31 (18.69)	**		*	*
DSP								
Place-response index	2	.49 (.28)	.49 (.26)	.53 (.27)				
Shortcut goals found	2	9.38 (3.60)	9.00 (3.67)	6.67 (2.74)	*		*	
Other								
SAQ	1,2	3.37 (1.03)	3.87 (1.00)	3.94 (1.08)	***	*	*	
SBSOD	0–3	4.80 (.95)	4.34 (.86)	3.93 (1.00)	***	*	*	*
MRT	0,2	35.94 (17.33)	30.82 (21.91)	18.06 (19.91)	***	*	*	*
WRAT-4	1–3	48.48 (3.50)	47.19 (4.21)	45.23 (4.67)	***		*	

Note. Results of the measures for each of the three pointing clusters, using the within-study clusters, but data are collapsed across all studies for which the measure was collected. Contrast significance determined based on whether the result of a *t* test was below $\alpha = .05 / 3 = .0166$. Study 0 refers to data collected and published in Weisberg and colleagues (2014). RMT = Route Membership Task; DSP = dual solution paradigm; SAQ = Spatial Anxiety Questionnaire; SBSOD = Santa Barbara Sense of Direction; MRT = Mental Rotation Test; WRAT-4 = Wide Range Achievement Test.
$^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$.

found that the three groups did differ, with integrators ($M = 48.48$, $SD = 3.50$) scoring higher than imprecise navigators ($M = 45.23$, $SD = 4.67$), $t(110) = 4.22$, $p < .001$, $d = 0.81$, but not non-integrators ($M = 47.19$, $SD = 4.21$), $t(139) = 1.95$, $p = .053$, $d = 0.33$. The imprecise navigators and non-integrators were marginally significantly different, $t(123) = 2.43$, $p = .017$, $d = 0.47$. These differences support the need to control for WRAT-4 scores in Studies 1 and 2, as we did.

Discussion

Overall, these results support the validity of the tripartite classification, by showing distinctive patterns of cognitive functioning, in which non-integrators are an intermediate group, sometimes indistinguishable from integrators but sometimes resembling imprecise navigators. Taxometric and cluster analyses, the SBSOD, and the model-building task support the group-based structure of the pointing data. In addition to establishing the stability of the Virtual Silcton paradigm (at least among undergraduate psychology students), these findings will aid future research that uses Virtual Silcton as a measure of navigation ability by providing benchmarks of navigation performance.

General Discussion

Taken together, the results from these three studies suggest a unified account of how navigation varies across individuals, with implications for the cognitive map debate and for practical work aimed at strengthening navigational proficiency.

Theoretical Implications

Evidence from the current studies suggests that the detail with which a representation is coded depends on individual differences in what Wolbers and Hegarty (2010) term offline spatial representations—memories for places, hierarchically structured encoding of environments, and navigation strategy. Approximately two thirds of navigators in our samples had sufficient working memory capacity to correctly encode the names and visual appearances of the eight buildings in the Virtual Silcton environment. Of these two thirds, some also learned information about the spatial positions of the buildings with sufficient precision to point between buildings which they had never directly traveled between (the integrators). Data from Virtual Silcton and the DSP suggest these navigators use (or are capable of using) a place-based strategy to integrate their spatial representations of environments. Among those who could not point between routes on Virtual Silcton, some had sufficiently high working memory capacity to encode all the buildings on the routes, but did not make inferences that allowed for between-route relationships to be made with any precision (the non-integrators). The imprecise navigators struggled encoding even the names and appearances of the eight buildings. Thus, it seems that some navigators are capable of forming cognitive maps, which integrate across routes, whereas others are limited by cognitive constraints that may be independent of mapping ability.

What is an integrated spatial representation? Although some scholars claim that spatial representations can have inherent map-like properties (e.g., Montello, 1998; Siegel & White, 1975; Tolman, 1948), the degree of literal analogy between a map and a cognitive map has been criticized (Foo et al., 2005; Shettleworth, 2009). One alternative proposal is that human spatial knowledge is not map-like but graph-like, consisting of a set of nodes and edges tagged with metric information (Chrastil, 2012; Chrastil & Warren, 2014). Another possibility is a map with biases (Uttal, Friedman, Hand, & Warren, 2010), inaccuracies, and nonveridical resolution. Either way, the Virtual Silcton paradigm provides evidence that at least some navigators have far more accurate spatial representations than the simple categorical or associative (or even incoherent) spatial representations posited by some investigators (Chrastil & Warren, 2014; McNamara, 1986; Tversky, 1992).

Given the central role of navigation in human ecology, why might some people be so bad? There are two points to consider. First, it is possible (and plausible) that humans naturally vary in their navigational proficiencies as a course and product of evolution. A variety of other essential survival skills nevertheless exhibit a range of ability levels (motherhood, face perception, etc.). Second, the modern environment may have spread out this natural variation to exacerbate differences between good and bad navigators. Similar to how some people eat too much sweet or fatty food, which is advantageous in the environment of evolutionary adaptation, but dangerous in the quantities that are now available, perhaps some people eat the spatial equivalent of calorie-rich food by blindly following a GPS. Others resist this temptation—they eat a balanced diet, or practice navigating from memory, or think about spatial directions. One recent investigation suggests that at least self-reported sense of direction is reducible to individual differences on personality dimensions (Condon et al., 2015). Whether the variety of navigation profiles described herein has implications for behavior, education, or health is not yet known.

Implications for Practical Application

Many neurological disorders affect the ability to navigate profoundly. Patients with Alzheimer's, schizophrenia, and depression, and even normally aging populations, experience difficulty in learning new environments or navigating familiar ones (Cherrier, Mendez, & Perryman, 2001; Gould et al., 2007; Moffat, Zonderman, & Resnick, 2001; Zawadzki et al., 2013). Many of these conditions differentially impact the hippocampus, which would yield impairment in the place-based strategies, but not necessarily response-based strategies. The present studies suggest that alternate methods of navigating environments that recruit the caudate instead of the hippocampus, or require learning a small number of locations, may benefit some of these navigators.

The different limitations of different groups of participants on the Virtual Silcton tasks suggest distinct applications for navigational aids. That some navigators (i.e., imprecise navigators) have difficulty encoding and recalling multiple buildings, focusing on one navigational goal at a time, or boosting working memory capacity may be the most fruitful method for improving navigation proficiency. On the other hand, the dissociation between strategy and success found in Study 2 suggests that options in navigational aids (such as GPS devices) should afford route-based or place-based modes of operation, so individuals can select the strategy they feel most comfortable with.

The present studies also introduce a virtual environment tool—Virtual Silcton—to study navigation, which can be widely used to study development, the role of gesture, or the effects of training. In particular, the tripartite division of navigators offers insight into what aspects of navigation training might benefit individual navigators the most. Training studies will be required to assess various methods of improving navigational proficiency, but underlying individual differences on different aspects of navigational tasks must be considered. The present studies suggest that one-size-fits-all solutions may fit no one.

Limitations and Future Directions

The current work takes a significant step forward in characterizing the cognitive and strategic correlates of individual differences in navigation proficiency, but much research is still necessary for a more accurate picture. One set of factors we cannot rule out entirely are differences in how the three groups of navigators explored the Virtual Silcton environment. Although we found in Study 3 that the three groups did not differ in how long they spent exploring Virtual Silcton, we did not investigate whether participants explored the environments differently in systematic ways (e.g., spent more time facing the buildings, looked in more directions). These should be the subjects of future studies. The current studies are correlational, so future research could vary the navigation tasks to address questions such as whether people with lower working memory capacity can still form accurate spatial representations of simple environments, or, by varying instructions, change the strategy people are inclined to adopt in learning the environment to determine whether learning strategy interacts with configural knowledge. In addition, the other components in Wolbers and Hegarty's (2010) model should be explored, such as individual differences in sensorimotor processing of the stimuli.

Conclusion

Individuals can and do learn their environments in different ways. These findings offer implications for theory—the cognitive map contains qualitative metric information—and practice—methods of treatment may be available for the variety of populations that suffer navigation impairment (e.g., in schizophrenia, Alzheimer's, and sometimes healthy people). The tasks used here, Virtual Silcton and the DSP, are part of an effort to establish a profile of navigational behavior. This allows researchers to map various navigational functions (e.g., landmark memory, path integration) to more general cognitive processes, potentially recasting individual differences in navigating as tapping into cognitive strengths (or avoiding cognitive weaknesses). Because navigation is a fundamental requirement of mobile organisms, studying its intricacies offers deep insights into the nature of cognition and aids in our understanding of how humans represent the outside world.

References

Allen, G. L., Kirasic, K. C., Dobson, S. H., Long, R. G., & Beck, S. (1996). Predicting environmental learning from spatial abilities: An indirect route. *Intelligence, 22,* 327–355. http://dx.doi.org/10.1016/S0160-2896(96)90026-4

Cherrier, M. M., Mendez, M., & Perryman, K. (2001). Route learning performance in Alzheimer disease patients. *Neuropsychiatry, Neuropsychology, and Behavioral Neurology, 14,* 159–168.

Chrastil, E. R. (2012). Neural evidence supports a novel framework for spatial navigation. *Psychonomic Bulletin & Review, 20,* 208–227. http://dx.doi.org/10.3758/s13423-011-0182-x

Chrastil, E. R., & Warren, W. H. (2014). From cognitive maps to cognitive graphs. *PLoS ONE, 9,* e112544. http://dx.doi.org/10.1371/journal.pone.0112544

Condon, D. M., Wilt, J., Cohen, C. A., Revelle, W., Hegarty, M., & Uttal, D. H. (2015). Sense of direction: General factor saturation and associations with the Big Five traits. *Personality and Individual Differences, 86,* 38–43. http://dx.doi.org/10.1016/j.paid.2015.05.023

Downs, R. M. (1981). Maps and metaphors. *The Professional Geographer, 33,* 287–293. http://dx.doi.org/10.1111/j.0033-0124.1981.00287.x

Epstein, R. A., Higgins, J. S., & Thompson-Schill, S. L. (2005). Learning places from views: Variation in scene processing as a function of experience and navigational ability. *Journal of Cognitive Neuroscience, 17,* 73–83. http://dx.doi.org/10.1162/0898929052879987

Foo, P., Warren, W. H., Duchon, A., & Tarr, M. J. (2005). Do humans integrate routes into a cognitive map? Map- versus landmark-based navigation of novel shortcuts. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 31,* 195–215. http://dx.doi.org/10.1037/0278-7393.31.2.195

Friedman, A., & Kohler, B. (2003). Bidimensional regression: Assessing the configural similarity and accuracy of cognitive maps and other two-dimensional data sets. *Psychological Methods, 8,* 468–491. http://dx.doi.org/10.1037/1082-989X.8.4.468

Furman, A. J., Clements-Stephens, A. M., Marchette, S. A., & Shelton, A. L. (2014). Persistent and stable biases in spatial learning mechanisms predict navigational style. *Cognitive, Affective & Behavioral Neuroscience, 14,* 1375–1391. http://dx.doi.org/10.3758/s13415-014-0279-6

Gould, N. F., Holmes, M. K., Fantie, B. D., Luckenbaugh, D. A., Pine, D. S., Gould, T. D., . . . Zarate, C. A., Jr. (2007). Performance on a virtual reality spatial memory navigation task in depressed patients. *The American Journal of Psychiatry, 164,* 516–519. http://dx.doi.org/10.1176/ajp.2007.164.3.516

Han, X., & Becker, S. (2014). One spatial map or many? Spatial coding of connected environments. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 40,* 511–531. http://dx.doi.org/10.1037/a0035259

Hanley, G. L., & Levine, M. (1983). Spatial problem solving: The integration of independently learned cognitive maps. *Memory & Cognition, 11,* 415–422. http://dx.doi.org/10.3758/BF03202457

Hartley, T., Maguire, E. A., Spiers, H. J., & Burgess, N. (2003). The well-worn route and the path less traveled: Distinct neural bases of route following and wayfinding in humans. *Neuron, 37,* 877–888. http://dx.doi.org/10.1016/S0896-6273(03)00095-3

Hegarty, M., Montello, D. R., Richardson, A. E., Ishikawa, T., & Lovelace, K. (2006). Spatial abilities at different scales: Individual differences in aptitude-test performance and spatial-layout learning. *Intelligence, 34,* 151–176. http://dx.doi.org/10.1016/j.intell.2005.09.005

Hegarty, M., Richardson, A. E., Montello, D. R., Lovelace, K., & Subbiah, I. (2002). Development of a self-report measure of environmental spatial ability. *Intelligence, 30,* 425–447. http://dx.doi.org/10.1016/S0160-2896(02)00116-2

Holding, C. S., & Holding, D. H. (1989). Acquisition of route network knowledge by males and females. *Journal of General Psychology, 116,* 29–41. http://dx.doi.org/10.1080/00221309.1989.9711108

Iaria, G., & Barton, J. J. (2010). Developmental topographical disorientation: A newly discovered cognitive disorder. *Experimental Brain Research, 206,* 189–196. http://dx.doi.org/10.1007/s00221-010-2256-9

Ishikawa, T., & Montello, D. R. (2006). Spatial knowledge acquisition from direct experience in the environment: Individual differences in the development of metric knowledge and the integration of separately learned places. *Cognitive Psychology, 52,* 93–129. http://dx.doi.org/10.1016/j.cogpsych.2005.08.003

Jacobs, L. F., & Menzel, R. (2014). Navigation outside of the box: What the lab can learn from the field and what the field can learn from the lab. *Movement Ecology, 2,* 3. http://dx.doi.org/10.1186/2051-3933-2-3

Jacobs, L. F., & Schenk, F. (2003). Unpacking the cognitive map: The parallel map theory of hippocampal function. *Psychological Review, 110,* 285–315. http://dx.doi.org/10.1037/0033-295X.110.2.285

Kuipers, B. (2000). The spatial semantic hierarchy. *Artificial Intelligence, 119,* 191–233. http://dx.doi.org/10.1016/S0004-3702(00)00017-5

Lawton, C. A. (1994). Gender differences in way-finding strategies: Relationship to spatial ability and spatial anxiety. *Sex Roles, 30*(11–12), 765–779. http://dx.doi.org/10.1007/BF01544230

Maguire, E. A., Gadian, D. G., Johnsrude, I. S., Good, C. D., Ashburner, J., Frackowiak, R. S. J., & Frith, C. D. (2000). Navigation-related structural change in the hippocampi of taxi drivers. *PNAS Proceedings of the National Academy of Sciences of the United States of America, 97,* 4398–4403. http://dx.doi.org/10.1073/pnas.070039597

Maguire, E. A., Woollett, K., & Spiers, H. J. (2006). London taxi drivers and bus drivers: A structural MRI and neuropsychological analysis. *Hippocampus, 16,* 1091–1101. http://dx.doi.org/10.1002/hipo.20233

Marchette, S. A., Bakker, A., & Shelton, A. L. (2011). Cognitive mappers to creatures of habit: Differential engagement of place and response learning mechanisms predicts human navigational behavior. *The Journal of Neuroscience, 31,* 15264–15268. http://dx.doi.org/10.1523/JNEUROSCI.3634-11.2011

McDonald, R. J., & White, N. M. (1994). Parallel information processing in the water maze: Evidence for independent memory systems involving dorsal striatum and hippocampus. *Behavioral & Neural Biology, 61,* 260–270. http://dx.doi.org/10.1016/S0163-1047(05)80009-3

McNamara, T. P. (1986). Mental representations of spatial relations. *Cognitive Psychology, 18,* 87–121. http://dx.doi.org/10.1016/0010-0285(86)90016-2

Meehl, P. E., & Yonce, L. J. (1994). Taxometric analysis: I. Detecting taxonicity with two quantitative indicators using means above and below a sliding cut (MAMBAC procedure). *Psychological Reports, 74* (3, Pt. 2), 1059–1274.

Meehl, P. E., & Yonce, L. J. (1996). Taxometric analysis: II. Detecting taxonicity using covariance of two quantitative indicators in successive intervals of a third indicator (MAXCOV procedure). *Psychological Reports, 78* (3c), 1091–1227. http://dx.doi.org/10.2466/pr0.1996.78.3c.1091

Moffat, S. D., Zonderman, A. B., & Resnick, S. M. (2001). Age differences in spatial memory in a virtual environment navigation task. *Neurobiology of Aging, 22,* 787–796. http://dx.doi.org/10.1016/S0197-4580(01)00251-2

Montello, D. R. (1998). A new framework for understanding the acquisition of spatial knowledge in large-scale environments. In R. G. Golledge & M. J. Egenhofer (Eds.), *Spatial and temporal reasoning in geographic information systems* (pp. 143–154). New York, NY: Oxford University Press.

Morris, R. G. M., Garrud, P., Rawlins, J. N. P., & O'Keefe, J. (1982). Place navigation impaired in rats with hippocampal lesions. *Nature, 297,* 681–683. http://dx.doi.org/10.1038/297681a0

Munn, N. L. (1950). *Handbook of psychological research on the rat; an introduction to animal psychology*. Oxford, UK: Houghton Mifflin.

Packard, M. G., & McGaugh, J. L. (1996). Inactivation of hippocampus or caudate nucleus with lidocaine differentially affects expression of place and response learning. *Neurobiology of Learning and Memory, 65,* 65–72. http://dx.doi.org/10.1006/nlme.1996.0007

Peters, M., Laeng, B., Latham, K., Jackson, M., Zaiyouna, R., & Richardson, C. (1995). A redrawn Vandenberg and Kuse mental rotations test: Different versions and factors that affect performance. *Brain and Cognition, 28,* 39–58. http://dx.doi.org/10.1006/brcg.1995.1032

Ploran, E. J., Rovira, E., Thompson, J. C., & Parasuraman, R. (2015). Underlying spatial skills to support navigation through large, unconstrained environments. *Applied Cognitive Psychology, 29,* 608–613. http://dx.doi.org/10.1002/acp.3135

Restle, F. (1957). Discrimination of cues in mazes: A resolution of the place-vs.-response question. *Psychological Review, 64,* 217–228. http://dx.doi.org/10.1037/h0040678

Ruscio, J. (2010). *Taxometric programs for the R computing environment: User's manual*. Retrieved from http://www.tcnj.edu/~ruscio/taxometrics.html

Schinazi, V. R., Nardi, D., Newcombe, N. S., Shipley, T. F., & Epstein, R. A. (2013). Hippocampal size predicts rapid learning of a cognitive map in humans. *Hippocampus, 23,* 515–528. http://dx.doi.org/10.1002/hipo.22111

Shettleworth, S. J. (2009). *Cognition, evolution, and behavior* (2nd ed.). New York, NY: Oxford University Press.

Siegel, A. W., & White, S. H. (1975). The development of spatial representations of large-scale environments. *Advances in Child Development and Behavior, 10,* 9–55. http://dx.doi.org/10.1016/S0065-2407(08)60007-5

Strauss, E. H. (2006). *A compendium of neuropsychological tests: Administration, norms, and commentary*. New York, NY: Oxford University Press.

Tolman, E. C. (1948). Cognitive maps in rats and men. *Psychological Review, 55,* 189–208. http://dx.doi.org/10.1037/h0061626

Tolman, E. C., Ritchie, B. F., & Kalish, D. (1946). Studies in spatial learning: Orientation and the short-cut. *Journal of Experimental Psychology, 36,* 13–24. http://dx.doi.org/10.1037/h0053944

Tversky, B. (1992). Distortions in cognitive maps. *Geoforum, 23,* 131–138. http://dx.doi.org/10.1016/0016-7185(92)90011-R

Unsworth, N., Heitz, R. P., Schrock, J. C., & Engle, R. W. (2005). An automated version of the operation span task. *Behavior Research Methods, 37,* 498–505. http://dx.doi.org/10.3758/BF03192720

Uttal, D. H., Friedman, A., Hand, L. L., & Warren, C. (2010). Learning fine-grained and category information in navigable real-world space. *Memory & Cognition, 38,* 1026–1040. http://dx.doi.org/10.3758/MC.38.8.1026

Vandenberg, S. G., & Kuse, A. R. (1978). Mental rotations, a group test of three-dimensional spatial visualization. *Perceptual and Motor Skills, 47,* 599–604. http://dx.doi.org/10.2466/pms.1978.47.2.599

Wechsler, D. (2003). *Wechsler intelligence scale for children-Fourth Edition* (WISC-IV). San Antonio, TX: Harcourt Assessment.

Wechsler, D. (2008). *Wechsler adult intelligence scale–Fourth Edition* (WAIS–IV). San Antonio, TX: NCS Pearson.

Weisberg, S. M., Schinazi, V. R., Newcombe, N. S., Shipley, T. F., & Epstein, R. A. (2014). Variations in cognitive maps: Understanding individual differences in navigation. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 40,* 669–682. http://dx.doi.org/10.1037/a0035261

Wen, W., Ishikawa, T., & Sato, T. (2011). Working memory in spatial knowledge acquisition: Differences in encoding processes and sense of direction. *Applied Cognitive Psychology, 25,* 654–662. http://dx.doi.org/10.1002/acp.1737

Wen, W., Ishikawa, T., & Sato, T. (2013). Individual differences in the encoding processes of egocentric and allocentric survey knowledge. *Cognitive Science, 37,* 176–192. http://dx.doi.org/10.1111/cogs.12005

Wilkinson, G. S., & Robertson, G. J. (2006). *Wide Range Achievement Test (WRAT-4)*. Lutz, FL: Psychological Assessment Resources.

Wolbers, T., & Büchel, C. (2005). Dissociable retrosplenial and hippocampal contributions to successful formation of survey representations. *The Journal of Neuroscience, 25,* 3333–3340. http://dx.doi.org/10.1523/JNEUROSCI.4705-04.2005

Wolbers, T., & Hegarty, M. (2010). What determines our navigational abilities? *Trends in Cognitive Sciences, 14,* 138–146. http://dx.doi.org/10.1016/j.tics.2010.01.001

Wolbers, T., Weiller, C., & Büchel, C. (2004). Neural foundations of emerging route knowledge in complex spatial environments. *Cognitive Brain Research, 21,* 401–411. http://dx.doi.org/10.1016/j.cogbrainres.2004.06.013

Woollett, K., & Maguire, E. A. (2011). Acquiring "the knowledge" of London's layout drives structural brain changes. *Current Biology, 21,* 2109–2114. http://dx.doi.org/10.1016/j.cub.2011.11.018

Zawadzki, J. A., Girard, T. A., Foussias, G., Rodrigues, A., Siddiqui, I., Lerch, J. P., . . . Wong, A. H. (2013). Simulating real world functioning in schizophrenia using a naturalistic city environment and single-trial, goal-directed navigation. *Frontiers in Behavioral Neuroscience, 7,* 180. http://dx.doi.org/10.3389/fnbeh.2013.00180

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