ORIGINAL RESEARCH ARTICLE
published: 02 December 2010
doi: 10.3389/fpsyg.2010.00214

We were also interested in characterizing, in detail, the particular pattern oest(02f>(ta)5(u3(r)12(e)-67(o)3()2(est(02e>8(a)-2(c)7st(029>(par)-17(

60 cm × 24 cm rectangle area on the screen. During each trial, the entire screen either looked like field terrain (in green) or like desert (sandy in yellow or red). Participants were told that the traveling cost rates were 1, 3, and 5 points per cm, respectively for the field, yellow desert, and red desert. They were also told that similar terrains would be used in the planning phase, where 200 points would equal US$1.

Feedback of the length and the points of the actual trajectory were given after each trial. To encourage precise movement, if the length of trajectory in a trial exceeded 1.08 times of the linear distance between the starting point and destination, the trial would be repeated immediately. Both successful and unsuccessful trials entered later analysis. t

The training gave participants practice in finger movement and allowed us to learn each participant's motor vials

For each participant, we examined whether the actual routes conformed to this straight-line heuristic. Given the points where an actual route intersected the desert,JETEMC 7s1d empoutehowtelcgd -5( )TJET

The difference of $(X_{in} + X_{out})/2$ between right-oriented and left–oriented trials gave a measure of their left–right bias. Participant P04 (right-handed) was biased 2.1 cm toward the left and the left–handed P06 was biased 0.9 cm toward the right.

We concluded that 10 out of 12 participants conformed to the LR heuristic.

Up–down symmetry heuristic

The starting point and the destination are symmetrically placed about the horizontal line bisecting the screen as are terrains. It is evident that the optimal route should have the same symmetry. Inspecting participants' actual routes by eye, we identified one and only one patterned violation of the symmetry that we refer to as *the one-turn bias* (illustrated in **Figure 3D**). Instead of having two symmetric turns at the two desert borders, respectively, the route has only one turn, at one of the borders. During inforbecause "the shortest distance between two points is a straight line". That is, the one-turn bias was a result of a misuse of the straight-line heuristic.

We computed the difference between X_{in} and X_{out} as an index of symmetry (**Figure 3E**). A one-tailed one-sample Student's *t*-test was performed on the difference for each participant. Seven participants' differences from zero were significant, implying a use of the one-turn bias. For the remaining five participants we could not reject the hypothesis that the routes they planned were symmetric.

We expected that the one-turn bias would reduce the participant's monetary gain in the route planning task. Other things equal, it might be that the larger the difference between X_{in} and X_{out}, the lower the participant's efficiency. To test this, we computed the Pearson's correlation between the absolute value of the difference between X_{in} and X_{out} and the efficiency for the 12 participants, $r = -0.46$, $p = 0.13$. The correlation was negative as expected but failed to reach significance probably because the number of participants (12) was small so that the effects of their differences in other aspects, e.g., the utility function (discussed next), made the effect of the one-turn bias less visible.

MODELS OF UTILITY

All but one participant failed to choose the least costly routes and half of the participants even failed to have symmetrical routes. However, the routes they planned did vary systematically with cost ratio and λ.

We considered the possibility that the systematic failures of route planning that we observed were due to non-linearities in participants' utility functions. Following (Luce, 2000, Eq. 3.18), we modeled the utility function for losses as a power function with parameter α.

The actual routes across the desert were made up of three line segments[3] $R = (l_{f1}, C_{f1}; l_d, C_d; d_{f2}, C_{f2})$. Where l_{f1}, l_d, l_{f2} respectively denote the lengths of the segments from the starting point to desert, within the desert, and from desert to the destination, C_f and C_d denote cost rates of the field and the specific desert (C_d/C_f is the cost ratio), and α is a free parameter.

We formulated two models of utility for the economic route planning task. The two models differed in how the task was framed (Kahneman and Tversky, 1979). In the first model, the perceived total cost of a route was assumed to be the sum of the cost of each segment transformed by the utility function.

$$U^-\left(l_{f1}, l_d, l_{f2}\right) = \left(C_f l_{f1}\right)^\alpha + \left(C_d l_d\right)^\alpha + \left(C_f l_{f2}\right)^\alpha \quad (2)$$

In the second model, the perceived total cost was the cost of a route that is of the same total length but is entirely in the field plus the extra cost of the segment that is in the desert,

$$U^-\left(l_{f1}, l_d, l_{f2}\right) = \left(C_f\left(l_{f1} + l_d + l_{f2}\right)\right)^\alpha + \left(\left(C_d - C_f\right) l_d\right)^\alpha \quad (3)$$

These two models and possible framings are not exhaustive, but they are plausible. The former model regards the desert and the field as separate cost sources, while the latter model counts the cost of the desert as added to that of the field[4]. We refer to the models as the *separate cost model* and the *added cost model*, respectively. The three heuristics discussed above still correspond to necessary properties of the optimal path under either model.

[3]Even for those participants who exhibited one-turn bias we could model their path as three line segments two of which were collinear.

Participants planned routes that were either up–down symmetrical or one-turn. In either case, the route could be captured by one variable, which we referred to as X_{plan}. For up–down symmetrical routes, we define $X_{plan} = (X_{in} + X_{out})/2$; for one-turn routes, we define $X_{plan} = \min(X_{in} + X_{out})$, that is, the horizontal coordinate of the turning point.

Concerning whether the route is up–down symmetrical or one-turn and whether the separate or added cost model is used, we now have four alternative models for the perceived cost: Symmetrical-Separate (SS), Symmetrical-Added (SA), One-turn-Separate (OS), One-turn-Added (OA). In each model, the perceived cost could be expressed as a function of the route parameter X_{plan} together with the utility parameter α.

We assume that in each specific condition of cost ratio and λ, participants chose the X_{plan} that minimized the perceived cost of the route. For each participant, we fitted the actual X_{plan} of the 10 conditions (2 cost ratio $\times$ 5 λ) with the four models one by one in the least-squares method. We set an upper limit of 3 for the fitted α since larger values produce little change in predicted behavior. As an index of goodness of fit, the proportion of data variance explained by each model is shown in **Table 1**. The maximum proportion of each participant is highlighted in bold. Except P12, all the maximum proportions were above 0.7, with a median of 0.85.

[4]The assumption of separate cost may incur a violation of dominance in the sense that a route could be preferred than another route even when the former has both a longer length and a larger proportion of length in the desert. The assumption of added cost avoids this problem.

Table 1 | Proportion of variance explained by different utility models.

Participant	Route symmetry	Model: SS	SA	OS	OA
P02	S	—	**0.82**	0.31	—
P03	S	—	**0.74**	0.11	—
P05	S	—	**0.78**	0.35	0.21
P06	S	—	**0.86**	—	0.70
P09	S	0.97	**0.97**	0.89	0.83
P01	O	0.55	0.57	**0.85**	—
P04	O	0.80	0.85	**0.95**	0.21
P07	O	—	**0.74**	—	0.15
P08	O	0.71	0.45	**0.87**	—
P10	O	0.77	0.76	**0.78**	0.09
P11	O	**0.98**	0.76	0.61	0.26
P12	O	—	—	**0.31**	—

Participants with symmetric routes are placed first (S denotes symmetrical. O denotes one-turn). The number in bold is the largest variance explained for any particular participant. The variance explained for entries marked "----" was indistinguishable from 0.

We found that most participants' choice of symmetrical or one-turn routes was consistent with their best model. For example, for P02 who had symmetrical routes, symmetrical model SA was the best model, which accounted for 82% of the variance. All the five participants with symmetrical routes was best fit with the SA model (which assumes a symmetrical route). Five of the seven participants with one-turn routes were best fit with the OS model (which assumes a one-turn route). This agreement validated our assumptions about the utility function. For the two participants who exhibited the one-turn bias but were best fit by a symmetrical model, we conjecture that they used the symmetrical model as an approximation to the one-turn model during the planning, possibly because the latter was easier to imagine.

Figure 4 shows the data and best fit of X_{plan} for each participant. The estimated α was less than one for five participants and greater than one for the remaining seven. We will discuss the interpretation of α in the Discussion.

BIOLOGICAL COSTS

It is possible that some of the participants chose a sub-optimal route or make only one turn because it would take less motor effort or require a shorter planning or movement time than would the optimal route. That is, participants might be trading off external economic costs with internal biological costs of effort or time (Trommershäuser et al., 2003a,b). We exclude these possibilities below.

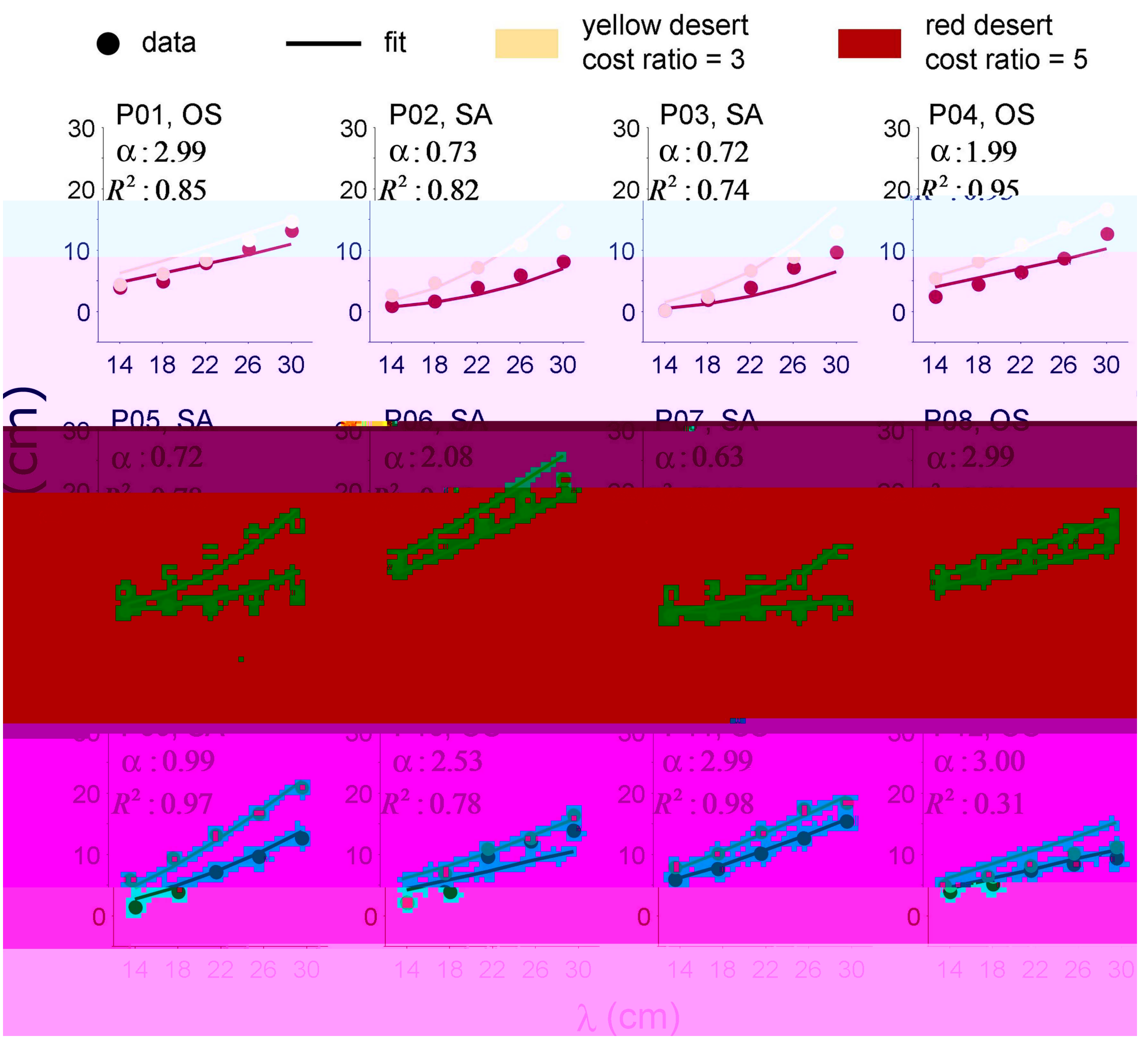

FIGURE 4 | Fit of utility model. The mean of the route parameter X_{plan} is plotted against λ. Yellow and red respectively correspond to cost ratios of 3:1 and 5:1, respectively. Dots denote data. Lines denote the model fit to data. Each panel is for one participant. The model shown for each participant is labeled as one of OS, OA, SS, SA. See text. It is the model that with the highest variance accounted for (R^2) for that participant. The R^2 is also shown. For models SS and SA. the models that assume symmetrical routes with three segments, X_{plan} denotes $(X_{in} + X_{out})/2$, where X_{in}, X_{out} are the horizontal coordinates of the position where each route enters and exits the desert, respectively. Models OS and OA are based on one-turn routes that violate symmetry. For these models, X_{plan} denotes X_{turn}, the horizontal coordinate of the single turning position. The free parameter of the utility function, α, estimated from the data for each participant, is shown. See text for full descriptions of the models.

correlation between movement time and the absolute value of $X_{out} - X_{in}$ across trials was –0.15, 0.02, 0.16, –0.04, 0.16, 0.17, –0.35, 0.16, –0.07, –0.01, –0.04, 0.01, respectively for P01–P12. Among them, only P06 had a significant but small positive correlation. However, since P06 did not exhibit the one-turn bias, the positive correlation probably rose out of chance. Thus the adoption of the one-turn bias was not the result of an attempt to minimize movement time.

DISCUSSION

We designed an economic task to investigate how well humans plan routes across landscapes consisting of two different terrains (field and desert) that imposed different costs per unit distance on the traveler. The cost per unit distance of the desert was either three times greater that of the field (yellow desert) or five times greater (red desert). Participants received monetary rewards that depended on the routes they selected. They were motivated to find the least costly route.

Viewed in the abstract, we are investigating spatial cognition

The evident usefulness of heuristics is to permit the traveler to narrow down the candidate routes before selecting the least expensive among those remaining. Our experimental design allows us to contrast overall maximization of reward and adherence to rules necessary but not sufficient for optimal performance.

We found that most participants correctly used the straight-line and LR heuristics. In real environments, with costs that gradually change across space, optimal routes are rarely straight lines. It is interesting that participants in our task, where maximum gain and maximum utility paths consist of straight-line segments, did select paths that were close to straight lines across uniform terrain.

However, almost half of the participants failed to follow the UD heuristic. Instead of choosing routes with two symmetrical turns at the borders of the desert, they chose routes with only one turn typically at an edge between field and desert (**Figure 3D**). As a consequence, one segment in the field and one segment in the desert were collinear, and comments during debriefing suggested that their failure was an over-generalization of the straight-line heuristic.

We also examined whether we could interpret participants' failures as a consequence of assigning non-linear utilities to costs incurred in each terrain. The heuristics described above were also necessary characteristics of any route maximizing utility. We compared the individual fits of four possible models that differed in heuristics used and estimated the parameters of the utility function for each participant separately.

In studies using numerical lotteries, the exponential parameter of the utility function is estimated to be less than one for most people (Luce, 2000), which implies that people may prefer a single large loss to several small losses that sum to the same value as the large loss. For example, Thaler and Johnson (1990) found that 75% of people preferred losing \$150 all at once to losing \$100 and then \$50. In our experiment, however, the number of participants with parameter values greater than 1 is slightly greater than the number of those with parameter values less than 1.

How would participants behave if they could actually walk within enlarged copies of our landscapes rather than just tracing a path? Previous research on route planning in full-scale landscapes has focused on the effect of impenetrable obstacles on route selection. The dynamical system model developed by Warren and colleagues (Fajen and Warren, 2003; Fajen et al., 2003) predicted routes in good agreement with human route selection while freely moving in landscapes with obstacles. The obstacle in their experiments was in the middle of the starting position and the destination. The predicted routes with obstacles deviated from those without obstacles only within a small range around the obstacle. That is, the walker would head straight toward the destination as if the obstacle was absent until he came very close to the obstacle. Their results suggest that routes are not fully planned ahead of time. While participants could readily plan each route as a whole in our experiment, the same cannot be said of the planning of extended routes in natural terrain.

In contrast to our results on the touch screen, the resulting routes described in Fajen and Warren (2003; Fajen et al., 2003) are typically curved and do not follow the straight-line heuristic even when alternative routes formed of line segments could be shorter and pass no closer to the obstacle. These deviations from linearity are possibly due to the absence of explicit costs on the length of the resulting route. It is plausible that participants prefer gently curved paths to piecewise linear paths with abrupt changes in direction due to the inertial costs associated with making sharp turns. If so, they may consider this biological cost (Trommershäuser, et al., 2003a,b) in planning routes and trade biological costs off against other costs. We conjecture that, with increasing costs per unit distance traveled, participants' route will more and more resemble a joined series of straight lines as the relative importance of biological costs diminishes. Research is needed to see whether this prediction is borne out and to determine how to develop models that predict human performance in full-scale economic landscapes containing terrains differing in cost.

The economic navigation task described here provided us with a tool to probe visual cognition, the use of spatial heuristics and distortions of cost by human route planners. The unambiguously defined payoffs permitted us to uncover human fallacies that might not be accessible through other approaches.

Given the importance of navigation in human life, the investigation of possible fallacies in human navigation deserves the same attention as the fallacies in human cognition (Arrow, 1958; Tversky and Kahneman, 1974).

In the present study we examined human navigation in terrains with different costs associated with different terrains. We could certainly consider how the cost structure of the environment interacts with factors known to affect navigation such as external representation of spatial information (Zhang, 1997) or gender difference (Kim et al., 2007).

In terms of biological foraging, the costs we considered were analogous to energy and the optimal routes planned minimized "energy". We could also consider route planning in environments where each unit of distance entailed a fixed risk. An animal traveling through heavily wooded terrain, for example, might avoid clearings precisely because crossing them entails a heightened risk of being observed by a predator, a risk that increases with time spent in the open. With this interpretation we could consider navigation problems where the terrain itself is uniform but the risks associated with different parts of the terrain are not, e.g., marine or aerial navigation (Hutchins and Lintern, 1995).

We have characterized human performance in terms of expected utility and adherence to heuristics, a computational theory corresponding to the first level of David Marr's hierarchy (Marr, 1982). The next step would be to develop a detailed algorithmic description (Marr's second level) of how humans plan routes across terrains differing in cost. As we noted above, heuristics serve to reduce the "search space", but the question remains as to how humans select one route from among those that remain.

The current experiment captures important aspects of the structure of navigation tasks in realistic terrains. Given a map and asked to plan a route of a few kilometers across terrain varying in cost (see **Figure 1**), the participant would be engaged in a task very similar to ours. The geometric reasoning involved is an important aspect of visual cognition. We do not claim that our conclusions will necessarily generalize to speeded tasks similar to ours or large-scale tasks involving routes across hundreds of meters or kilometers. We conjecture that they will and, in any case, our work provides clear, testable hypotheses relevant to these richer, more complex problems.

REFERENCES

Arrow, K. J. (1958). Utilities, attitudes, choices: a review note. *Econometrica* 26, 1–23.

Battaglia, P. W., and Schrater, P. R. (2007). Humans trade off viewing time and movement duration to improve visuomotor accuracy in a fast reaching task. *J. Neurosci.* 27, 6984–6994.

Brainard, D. H. (1997). The psychophysics toolbox. *Spat. Vis.* 10, 433–436.

Dean, M., Wu, S., and Maloney, L. (2007). Trading off speed and accuracy in rapid, goal-directed movements. *J. Vis.* 7, 1–12.

Di Fiore, A., and Suarez, S. (2007). Route-based travel and shared routes in sympatric spider and woolly monkeys: cognitive and evolutionary implications. *Anim. Cogn.* 10, 317–329.

Fajen, B. R., and Warren, W. H. (2003). Behavioral dynamics of steering, obstacle avoidance, and route selection. *J. Exp. Psychol. Hum. Percept. Perform.* 29, 343–362.

Fajen, B. R., Warren, W. H., Temizer, S., and Kaelbling, L. P. (2003). A dynamical model of visually-guided steering, obstacle avoidance, and route selection. *Int. J. Comput. Vis.* 54, 13–34.

Gallistel, C. R. (1990). *The Organization of Learning*. Cambridge, MA: MIT Press.

Gallistel, C. R., and Cramer, A. E. (1996). Computations on metric maps in mammals: getting oriented and choosing a multi-destination route. *J. Exp. Biol.* 199, 211–217.

Gärling, T., Böök, A., Lindberg, E., and Arce, C. (1991). Evidence of a response-bias explanation of non-euclidean cognitive maps. *Prof. Geogr.* 43, 143–149.

Gärling, T., and Gärling, E. (1988). Distance minimization in downtown pedestrian shopping. *Environ. Plan. A* 20, 547–554.

Golledge, R. (1995). "Path selection and route preference in human navigation: a progress report," in *Spatial Information Theory: A Theoretical Basis for GIS*, eds A. U. Frank and W. Kuhn (New York: Springer-Verlag), 207–222.

Hutchins, E., and Lintern, G. (1995). *Cognition in the Wild*. Cambridge, MA: MIT Press.

Janson, C. (2007). Experimental evidence for route integration and strategic planning in wild capuchin monkeys. *Anim. Cogn.* 10, 341–356.

Kahneman, D., and Tversky, A. (1979). Prospect theory: an analysis of decision under risk. *Econometrica* 47, 263–291.

Kim, B., Lee, S., and Lee, J. (2007). Gender differences in spatial navigation. *World Acad. Sci. Eng. Technol.* 31, 297–300.

Luce, R. D. (2000). *Utility of Gains and Losses: Measurement – Theoretical and Experimental Approaches*. London: Lawrence Erlbaum, 80–84.

MacGregor, J. N., Ormerod, T. C., and Chronicle, E. P. (2000). A model of human performance on the traveling salesperson problem. *Mem. Cognit.* 28, 1183–1190.

Marr, D. (1982). *Vision: A Computational Investigation into the Human Representation and Processing of Visual Information.* New York: Freeman.

Milton, K. (2000). "Quo vadis? Tactics of food search and group movement in primates and other animals," in *On the Move: How and Why Animals Travel in Groups*, eds S. Boinski and P. A. Garber (Chicago: University of Chicago Press), 375–417.

Pelli, D. G. (1997). The videotoolbox software for visual psychophysics: transforming numbers into movies. *Spat. Vis.* 10, 437–442.

Säisä, J., and Gärling, T. (1987). Sequential spatial choices in the large-scale environment. *Environ. Behav.* 19, 614–635.

Shepard, R. N. (1975). "Form, formation, and transformation of internal representations," in *Information Processing and Cognition: The Loyola Symposium*, ed. R. L. Solso (Hillsdale, NJ: Lawrence Erlbaum), 103–117.

Stephens, D. W., and Krebs, J. R. (1986). *Foraging Theory*. Princeton, NJ: Princeton University Press.

Teghtsoonian, M. (1965). The judgment of size. *Am. J. Psychol.* 78, 392–402.

Thaler, R. H., and Johnson, E. J. (1990). Gambling with the house money and trying to break even: the effects of prior outcomes on risky choice. *Manage. Sci.* 36, 643–660.

Tolman, E. C. (1948). Cognitive maps in rats and men. *Psychol. Rev.* 55, 189–208.

Trommershäuser, J., Maloney, L. T., and Landy, M. S. (2003a). Statistical decision theory and the selection of rapid, goal-directed movements. *J. Opt. Soc. Am. A* 20, 1419–1433.

Trommershäuser, J., Maloney, L. T., and Landy, M. S. (2003b). Statistical decision theory and trade-offs in the control of motor response. *Spat. Vis.* 16, 255–275.

Tversky, A., and Kahneman, D. (1974). Judgment under uncertainty: heuristics and biases. *Science* 185, 1124–1131.

Valero, A., and Byrne, R. (2007). Spider monkey ranging patterns in Mexican subtropical forest: do travel routes reflect planning? *Anim. Cogn.* 10, 305–315.

Vickers, D., Butavicius, M., Lee, M., and Medvedev, A. (2001). Human performance on visually presented traveling salesman problems. *Psychol. Res.* 65, 34–45.

Wiener, J. M., Lafon, M., and Berthoz, A. (2008). Path planning under spatial uncertainty. *Mem. Cognit.* 36, 495–504.

Yost, J. A., and Kelley, P. M. (1983). "Shotguns, blowguns and spears: the analysis of technological efficiency," in *Adaptive Responses of Native Amazonians*, eds R. B. Hames and W. T. Vickers (New York: Academic Press), 189–224.

Zhang, J. (1997). Distributed representation as a principle for the analysis of cockpit information displays. *Int. J. Aviat. Psychol.* 7, 105–121.

Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Received: 16 August 2010; accepted: 10 November 2010; published online: 02 December 2010.

*Citation: Zhang H, Maddula SV and Maloney LT (2010) Planning routes across economic terrains: maximizing utility, following heuristics. Front. Psychology **1**:214. doi: 10.3389/fpsyg.2010.00214*

This article was submitted to Frontiers in Cognitive Science, a specialty of Frontiers in Psychology.