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TO THE NORTH COAST OF DEVON: COLLABORATIVE NAVIGATION WHILE EXPLORING UNFAMILIAR TERRAIN

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Navigation—knowing where one is and finding a safe route—is a fundamental aspect of all exploration. In unfamiliar terrain, one may use maps and instruments such as a compass or binoculars to assist, and people often collaborate in finding their way. This paper analyzes a group of people driving a humvee from a base camp to the north coast of Devon Island in the High Canadian Arctic. A complete audio recording and video during most stops allows a quantitative and semantic analysis of the conversations when the team stopped to take bearings and replan a route. Over a period of 2 hours, the humvee stopped 20 times, with an average duration of 3.15 min/pause and 3.85 min moving forward. The team failed to reach its goal due to difficult terrain causing mechanical problems. The analysis attempts to explain these facts by considering a variety of complicating factors, especially the navigation problem of relating maps and the world to locate the humvee and to plan a route. The analysis reveals patterns in topic structure and turn-taking, supporting the view that the collaboration was efficient, but the tools and information were inadequate for the task. This work is relevant for planning and training for planetary surface missions, as well as developing computer systems that could aid navigation.

INTRODUCTION: PRACTICAL AND SCIENTIFIC OBJECTIVES

During Apollo lunar traverses the astronauts relied on CapCom, a Mission Control point of contact in Houston, to help them navigate and use their time wisely. Until roads

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are built and signs deployed, future lunar traverses will pose the same navigation difficulties encountered in Apollo, especially when exploring new areas. Even robotic teleoperations from earth will require teams to relate imagery to their maps and route plans. Consequently, it will be useful to better understand how people navigate using maps and what problems they encounter in coordinating what they see, interpret, and say when driving a vehicle in hazardous terrain.

In particular, Apollo's lunar traverses illustrate that detours are often required when the terrain is unfamiliar and irregular, and these detours necessitate repeatedly re-establishing one's location and replanning a route. This problem occurs despite learning to recognize and name landmarks (such as craters) from photographs, as exemplified while driving the rover in Apollo 17[1]:

146:22:32 Gene Cernan: Look at that. Right on the southeastern ...

146:22:34 Jack Schmitt: Now, wait a minute.

146:22:35 Cernan: ...(Correcting himself) southwestern rim.

146:22:36 Schmitt: Yeah, yeah.

146:22:37 Cernan: (Perhaps looking at cuff checklist #22) Yeah, because Horatio's got to be on our right. Well, wait a minute, doggone it.

146:22:41 Schmitt: It's not Horatio, is it?

146:22:43 Cernan: Well, we're at 094, 1.7.

146:22:46 Bob Parker (CapCom): Stand by. (Pause)

146:22:52 Schmitt: No, I think that's Camelot. Horatio didn't...

146:22:53 Cernan: That's too...That's too...

146:22:54 Schmitt: ...have blocks that far up the rim.

146:22:55 Cernan: ...Let me...Yeah, let me look in the bottom. I'll tell you. I remember.

146:22:58 Schmitt: Yeah.

146:23:00 Parker: That kind of sounds like Camelot to us. ...

Even using today's technologies like a global positioning system (GPS) that might pinpoint location automatically, a route suitable for the mobility of the transportation vehicles and robots must still be found. Routes must adapt to local conditions (e.g., cliffs and loose rocks) and therefore looking ahead during travel is required. Jumbled lunar terrain required many detours[2]:

142:26:25 Cernan: We're doing a little zig-zag navigation. I literally came up a slope at about a heading of 240 (WSW). We couldn't get through the actual turn to the south because there is a big crater right at the foot of it. So we're just making our way through some relatively local undulating slopes that get pretty steep, but it seems to be no problem.

In such circumstances, explorers need to articulate their location hypotheses and route plans to each other:

142:31:58 Cernan: Jack, I'm going to head right along this ridge because I think that's the depression we were talking about.

142:32:01 Schmitt: Yep, that's Nansen down there.

142:32:02 Cernan: Where are you looking? Right there?

142:32:04 Schmitt: I think, right below...

142:32:06 Cernan: I think you're right. I think that's it. Let me get over here, and then I'll head a little bit to the south.

142:32:12 Schmitt: Yeah, we're a little more west, I think, than we intended to be....

142:33:29 Cernan: Bob, my best guess - let's see, 077, 7.7, 6.6 - is that we're coming up on the northern side of Nansen.

An external assistant, such as CapCom, using perhaps different maps and lacking the astronauts' point of view, as well as not seeing their gestures, must sometimes struggle to follow along[3]:

144:22:22 Schmitt: I've sort of lost track (of the two bright craters)...

144:22:23 Cernan: We're about there (pointing at the map).

144:22:24 Parker: I think we expected you guys to be a little bit farther north...

144:22:26 Cernan: I think we want to be more to the left.

144:22:26 Parker: ...We were guessing a heading (means "reading") of 080 for the bearing (to the LM) which really kind of says you were going a bit farther north than this.

[Parker is confused[††]. 080 was the bearing at the cancelled LRV stop. Houston estimates that Station 3 will be at 089/6.1. Gene (Cernan) is currently at 087/5.9, a short distance southeast of where they want to be.]

Such interactions raise questions about automating CapCom's navigational role. If Bob Parker became confused when relating the current route to the plan and adjusting the plan, how could a computer program do better? Smaller robots might find a way automatically or through teleoperation from a base camp, but such routes might prove impassable for larger vehicles. Whether we are considering people exploring or robotic scouts or some combination, we need to learn much more about navigation in unfamiliar terrain so we can build the right tools and adopt practical operations procedures. For example, is a crew of two likely to be so overburdened that an external CapCom is necessary? Could a computer assistant automate some of these navigation tasks or at least help CapCom follow along?

Analyzing the historical record of Apollo traverses is an excellent way to understand the navigation problems we will encounter on the moon and Mars.[4] Studying exploration in unfamiliar terrain on earth, particularly in lunar and mars analog topographies, provides another opportunity, which is the approach of this paper. We study people handling serious location and route problems, focusing on the strengths and limitations of their decision making and communication practices.

The present study involves two scientists driving a humvee accompanied by two "scouts" on all-terrain vehicles (ATVs), carrying out an operational test in unfamiliar terrain to the north coast of Devon Island in the Canadian High Arctic. This group

[††] This italicized note was inserted by Eric M. Jones, the editor of the ALSJ.

constitutes a small "away team," on a one night trip from base camp. To replicate a protocol used on an earlier humvee trip, in which the scouts are simulating robots, GPS is used only to establish waypoints and record progress, not to navigate. The experience of this group reveals that GPS would have saved a great deal of time in locating the humvee, but would not have been sufficient for finding a safe and efficient route.

This paper approaches the humvee trip from two perspectives: as an analog mission report with practical implications for planetary exploration and as basic research in cognitive science. The analysis presented here will straddle these practical and scientific perspectives, on the one hand seeking to explain the outcome of the operational test and lessons learned, and on the other hand, to explore the data in an open way to learn about decision making dialogues during a navigation task.

The scientific study of navigation involves investigation in natural work settings, recording teamwork, and relating diverse perceptual cues, gestures, and artifacts (maps and instruments). For these reasons, the problem of group navigation was mostly ignored in psychology until researchers took seriously that cognition is *situated* (located physically and socially conceived), *distributed* (among people, computational devices, and modalities of representation such as gesture and speech), and *interactive* (involving feedback on different levels with other people and machines).[5] Chase and Chi[6] pioneered the study of spatial reasoning in navigation by relating routes to the hand-drawn maps of taxi drivers. Hutchins work[7,8] is probably the most well-known synthesis of situated cognition issues in a navigation setting, particularly his studies of an airplane cockpit.

As the Apollo transcripts make obvious, the teamwork of navigation can involve a complex dance between pilot and co-pilot, involving looking, pointing, describing, and questioning. Such exchanges, called *turn-taking*, have been formalized in the field of social linguistics since the 1970s.[9] The data collected in the humvee affords studying how the sequence of topics relates to different speakers. The speakers have different roles in driving and navigating, and this is manifest by how they focus on the world and the map, as they coordinate locating where they are and finding a route.

The present investigation is not an experiment with pre-defined variables and hypotheses. Rather, as much as the trip for the geologist and biologist involved exploring new terrain, the trip was also exploratory for the cognitive scientist. One might call this a "natural experiment," in the sense that the scouting protocol involved well-defined goals, players, communications, and limited interaction with the outside world. On the other hand, the trip was not *designed* to produce useful information about decision making, cognitive processes in using aerial photographs, or teamwork. Rather, such issues and their relevance were discovered along the way, in the manner of geologists and biologists discovering in the field materials and patterns relevant to their interests. Hence, the analysis of the navigation dialogues includes a strong classificatory aspect of sorting through data to find statistically significant patterns.

The humvee pilot and navigator thought they would arrive at the north coast by midnight; their appraisal of the task was incorrect. This becomes the starting point of our study of their decision making and communication practices. Using the audio and photographic record, we work backwards to analyze the outcome of traverse and how this relates to individual and group decisions. Thus a central research question of this paper is, what can we learn about the difficulties of the navigation task from the dialogues in the humvee?

In our analysis, we find that the excursion suffered from lack of information (both locally and globally in the route). Perhaps intentionally, to carry out the experimental route-finding protocol, they did not reflect on trends and the impact of recurrent problems on the overall goal to adopt a different strategy. From these difficulties we can posit planning, route-mapping tools, and alternative protocols (e.g., different scouting methods) that might have ensured success in reaching the coast.

Regarding our practical concern with planetary exploration, understanding navigation is directly relevant to an ongoing research project, called Mobile Agents. Using the rubric of "automating CapCom"[10,11], we are developing computer agents that astronauts can voice command during a extravehicular activity (EVA) to control devices (e.g., cameras, robots), store and access EVA data (e.g., name places and comment on photographs), and receive location, procedural, and schedule advice. During such speech interactions, the computer system must "take turns" in a way that follows conventional patterns, such as not interrupting people when they are talking to each other, respecting authority[12], confirming commands and signaling problems, and making contextual inferences.[13] Related robotic research has considered how to develop "conversational agents" with informative gaze behavior (e.g., looking toward the listener).[14] Analysis of the pilot-navigator discourse may be relevant for constructing a simulation[15] of the navigation practice of the team, which could in turn be used to specify and test an agent that provides navigation assistance.

Subsequent sections of this paper describe the experimental setting and recording methods, hypotheses about the outcome of the operational test, an overview of timing and topics salient in the data, and a work practice analysis that characterizes the navigation discourse as it relates to route decision making. The paper concludes with a summary of the results and implications for future work.

EXPERIMENTAL SETTING: A HUMVEE OPERATIONAL TEST

This navigation experiment was part of the annual Haughton-Mars Project expedition.[16] The humvee pilot, identified in this paper as B, had previously led a group a week earlier to cross Devon Island using aerial maps, bringing the humvee about 74 km (40 nautical miles) from the west coast to base camp. The intention now was to make an overnight trip to the north coast of Devon Island, about 20 km away, to reach the gullies (generally ice-filled cliff ravines) investigated by helicopter in 2001. This traverse was part of a plan to conduct tests of the vehicle over several field seasons, to learn its operating characteristics, issues in navigation, habitability of the vehicle, and so forth. By yielding a great deal of such information, the operational test reported here was a success.

The group held a planning meeting on Tuesday July 22, 2003 to configure the navigation process. It was decided to replicate the method used in navigating from the west coast, with a person on an all terrain vehicle (ATV) scouting ahead of the humvee. The pilot (B) and co-pilot (G) would ride up front; the observer (the first author) would sit between with cameras and audio-recorder; two ATV riders would scout, one nearby to show firmness of the ground and one further to anticipate the route.

The chosen navigation method assumes that GPS is not available; instead location is determined by relating geographic features (hills, ravines, and permanent snow patches) to black and white aerial photographs (Figures 1 and 2) that were mostly taken in 1958-59 from an altitude of about 9 km (30,000 ft). The spatial resolution (smallest identifiable feature) in these photographs is approximately 4 m (i.e., we can spot boulders 4 m across, but none of the smaller ones unless they stand out against their background by albedo, in which case they could be as small as 2 m across). A topographic map was available, but was used primarily to plan the initial route on the aerial photos.

The navigation process involved: 1) determining the humvee's location with respect to aerial photographs (referred to as maps; mostly managed by G), 2) learning about the local area (from the ATVs driving in front of the humvee, one nearby to indicate wet areas, the other more distant to scout routes), 3) planning a route in the world by integrating photo and local information with what is visible from the humvee (B's decision based on G's advice), and 4) navigating local obstacles with respect to the chosen plan (B's task as driver).

The group of five departed late afternoon July 24. The discourse data and analysis we present comes from the initial 2 hours of route finding; the outcome analysis considers as well the interactions with the scouts.

The observer sat between B and G in a makeshift seat. The entire trip was audio recorded, using an mini-disc (MD) digital recorder. The microphone dangled between B and G (subject to some wind noise when windows were open). The initial route planning and most conversations were video-recorded with a hand-held mini-digital video (DV) recorder using 90 minute tapes. Both the video and sound quality are excellent. A digital wide-angle camera was used to record the general setup (Figure 1). Photographs and video still frames were recorded periodically (Figure 2).

PROBLEM: WHY DIDN'T THE GROUP REACH THE COAST?

As mentioned, the objective of the operational test was to learn about using the humvee for exploration. For this purpose, the group chose the goal of reaching the north coast of Devon Island.

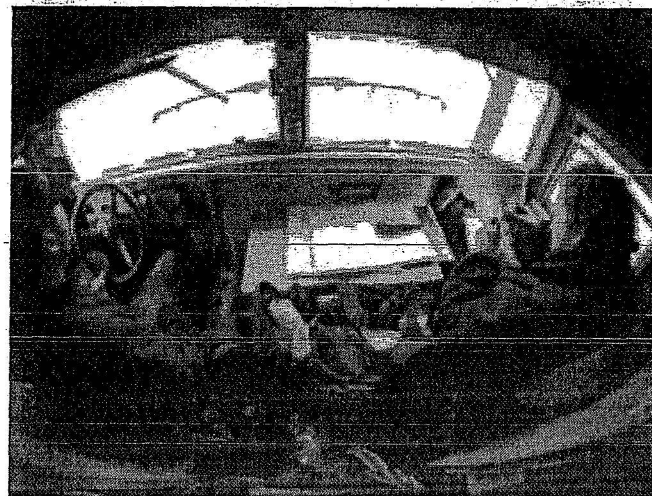

Figure 1. Humvee cockpit with B on left, G on right, maps and aerial photos shared in the middle. (Photo: W. Clancey/NASA Haughton Mars Project)

Figure 2. B and G determine where they are and where they want to go. (Photo: W. Clancey/NASA Haughton Mars Project)

Departure was delayed until after 5 PM, with midnight as a hopeful target for arrival. With the Arctic summer sun, it would remain light through the night and the group was self-sufficient for food and shelter, so stopping anywhere would be acceptable. The weather was mediocre, cloudy with cold winds and periodic light showers.

Two factors are most salient in the outcome of the traverse: First, an inappropriate route was chosen (after considerable deliberation), which caused a mechanical failure that necessitated spending the night about 6 km (linear distance) from base camp. Second, insufficient time was available for the trip, necessitating the group to turn back at noon the second day, before reaching the objective.

In this section we consider decisions made during preparation that affected the traverse, recurrent issues that arose during the trip, and hypotheses explaining the outcome, which are examined subsequently in the data analysis.

Preparation decisions

During planning discussions at several meetings prior to the humvee traverse, the group carefully articulated their individual objectives and constraints. These included:

- research (gullies, general exploration, experimental scouting protocol)
- safety (on traverse and affect of group's absence on rest of the camp)
- logistics (e,g., number of people who can sleep inside humvee)
- comfort (e.g., don't ride ATV in bad weather such a long distance)
- maintenance (of humvee and ATVs)
- other camp activities (e.g., phone calls, other camp commitments, media visits, ongoing communications experiments)
- documentation (the scouts included a cinematographer and writer)

The consensus was that all objectives had to be accommodated, perhaps through some adjustment of external constraints (e.g., rescheduling a media event). The weather introduced some uncertainty that probably contributed to the lack of a committed departure time.

Recurrent issues during trip

During the trip, the group was strongly focused on the task at hand. The recurrent issues included:

- Where are we?
- What route should we follow?
- Are obstacles ahead on the present path (e.g., boulders, mud, steep hills)?
- Where are the scouts and what are they doing?
- How could the scouts be helping better?

These issues are represented formally in the analysis of the navigation dialogues.

Hypotheses: Possible causes for not reaching the coast

After considering the data and experience in some detail, we suggest the following possible causes influencing the outcome of the trip. At this point, these are not conclusions, but *hypotheses* that analysis may support or refute. Three factors are posited at the top level: 1) The *terrain* made the trip impossible using the humvee with tracks; 2) The *time available* was insufficient, given the terrain and the navigation method; and 3) The *navigation method* was inadequate, given the terrain and travel time available. The time and method factors in turn have underlying, root causes to be considered.

- ***Terrain inappropriate for track humvee:*** Mechanical failure was caused by small rocks becoming caught in the humvee's tracks. These effects were possibly underestimated because earlier in the month the terrain was wetter and mud was the primary concern. This hypothesis claims that regardless of the location and route-finding practice used by the crew or time available, using tracks the humvee would not be able to make this trip safely.

- ***Insufficient time available for the trip:*** Departing at 5 PM allowed seven hours to travel 20 km. The logged location after about one hour was 5 km (linear distance) from camp, which is consistent with the plan. However, including the additional distance traveled until turn around on the second day, the group covered about 10 km (linear) in five hours (2 km/hr). Consequently, to reach the coast (20 km) might have required 10 hours. This hypothesis claims that given the terrain and navigation method, the trip could not be done in the available time. The root causes include:

    - *Miscalculation:* The 74 km trip from the west coast two weeks earlier required several days (with an approximate linear rate of 4.5 km/hr). An assumption might have been made that the northern route was better, as the seasonal mud had dried and there were no rivers to cross. Thus, even though the same navigation protocol would be used, it was tacitly assumed that travel would be at least as fast on this trip.

    - *Higher priority goals:* Other goals caused the group to leave late in the day and required them to return by early afternoon the next day. These concerns included lack of time for media visitors to meet with the humvee group participants, ongoing communications tests that required the humvee to be in camp, and an important incoming phone call (that necessitated being at base camp). Furthermore, spare parts for the humvee arrived unexpectedly, and it was decided to use them for maintenance prior to departure.

- ***Navigation method was inadequate:*** This hypothesis claims that assuming that the terrain afforded a safe route for the humvee using tracks, the available time would have been sufficient if the location and route-finding method were improved. This hypothesis has several interacting root causes:

    - *Aerial photographs were insufficient for navigation:* The photographs (taken at 30,000 feet) are difficult to relate to the visible terrain. Thus, the humvee was moving faster than the navigator could track their location, necessitating frequent stops. Also, the task might have been sufficiently difficult that it required the pilot's assistance. The navigator may have been preoccupied by locating the humvee, unable to devote sufficient time to route planning.

- *Route needed to be planned more globally:* Local obstacles were leading to a chain of long detours, which introduced uncertainty in the overall route, making it difficult for the distant scout to stay on the humvee's path.

- *Scouts didn't provide needed local obstacle and route information:* For example, they were not properly placed, not communicating/coordinating ~~with navigator appropriately, misinterpreting terrain affects on humvee,~~ and were impaired by weather.

How should the analysis proceed, given the interaction of these factors? One could speculate that if the humvee were using wheels instead of tracks, then the time available and navigation method might have been sufficient. But regarding the terrain, one could also argue that the west coast traverse demonstrated that the humvee can get through Devon Island's terrain, so it remains of interest to know how to navigate better with tracks. Although we do not know what difficulties lay between the stopping point and the coast, the recorded conversations suggest that an alternative route could have been found to circumvent the terrain that caused mechanical failure.

Regarding the time available, the expediencies of the short summer season made attempting the operational test more advantageous than canceling, even if the time was short. One could argue that 4-5 km/hr (linear) was a good estimate, and if a better route had been found, would have been sufficient.

Thus, although it is quite possible that wheels or more time would have enabled the group to reach the coast, our analysis of the data will be most productive if we focus on the navigation method. To this end, subsequent sections provide an overview of the data, followed by analysis of the navigation method and conclusions.

DATA OVERVIEW: TIMING AND TOPICS

The audio and video recordings made during the traverse provide the main source of information for evaluating hypotheses about the use of time and how decisions were made. As stated in the introduction, a related scientific motivation in analyzing the dialogue is to learn what aspects of the task are difficult, thus causing delays or contributing to non-optimal decisions. This section describes the basic analysis method and the broad facts and patterns it reveals.

~~The audio recordings of July 24 from 17:00 to 20:00 were transcribed using a~~ spreadsheet. Columns record the start time of a passage, the status of the vehicle (moving, stopped), the duration of the passage (computed using Visual Basic macros), and the transcribed text. The initial analysis determined that between 17:20 (when the group departed base camp) and 19:40 (when the mechanical problem developed), the humvee was stopped 20 times for an average duration of just over 3 minutes (Table 1). Perhaps surprisingly, during nearly half of traverse the humvee was stopped, and the average time moving between stops was under 4 minutes. Subsequent analysis is directed at understanding this pattern and what was happening during the pauses.

Table 1: Comparison of movement and paused durations on leaving camp

EVENT	COUNT	TOTAL TIME (h:mm)	AVERAGE DURATION (minutes)
Pause	20	1:03	3.15
Moving forward	20	1:17	3.85

To carry the analysis forward, three additional columns were added to the spreadsheet: Individual rows for each statement "topic" (a categorization of what is being said), the person introducing the topic (the pilot, designated as B, or the navigator, G), and the topic category. Four general topics were identified:

- WORLD=>MAP: Identify current location or salient landscape feature on aerial photo
- MAP=>WORLD: Find salient aerial photo feature in landscape
- ROUTE ON MAP: Determine general route in the aerial photo
- ROUTE IN WORLD: Determine target heading and route in the landscape

B and G engage in other shared activities, indicated by the topics WORLD and PROCEDURAL in the transcripts (note that B's remarks are always in parentheses):

- WORLD: Establishing a shared feature in the world, e.g., G: "Do you see where that first snow bank is <pointing out right window> (B: which one?) << open window>> first one to the left <pointing> (B: right, the big thick one?) yeah, (B: okay)"
- PROCEDURAL: Meta-topics, e.g., indicating an interest in stopping, positioning the scouts for providing useful information, relating the planned path to the actual route.

Note that the dialogue has been *segmented* into groups of utterances (sentences) that are about a single topic, as defined above, constituting the unit of analysis. Thus, the analysis of turn-taking concerns *topic exchange*, with the person who introduces a topic called the *actor*. Each topic is sometimes called a "statement" here, though it often includes several utterances (ranging from sentences to single words, most commonly, "yeah"). Within each topic segment in the dialogue one can find a form of turn-taking from one utterance to the next, called *speaker exchange,* which is not the concern of this analysis. Although the original work on turn-taking[9] examines patterns independent of the topic, our interest is precisely the opposite, primarily focusing on topic relations and secondarily on correlations with the speaker. In particular, we want to first understand the patterns of topic relationships (i.e., recurrent sequences) and then how the speakers take turns within these sequences.

On reviewing the audio transcripts, it was determined that the numerous references to "this" and "that" could not be understood without examining the video recording. Thus, the entire transcript was reviewed and further annotated to indicate where B and G were pointing. This analysis revealed that the dialogue between B and G concerning the aerial maps and route, which was the purpose of nine of the 19 stops, could be classified simply; the detailed analysis below focuses on their interaction during these nine stops. The remaining ten stops included: one near the beginning when a camera man swapped places with G; three pauses to log information; one call from base camp; and one rest break (7 min.). In addition there are four interactions with the scouts, including 18 min. of the final 24 minutes.

Figure 3 shows the entire first day traverse graphically. Notice that the stops become much longer in the last third. This is when the difficult terrain was encountered, which we will examine subsequently. Other patterns to notice are the relatively long movement periods in the first two-thirds of the traverse, as well as nine stops of one or two minutes.

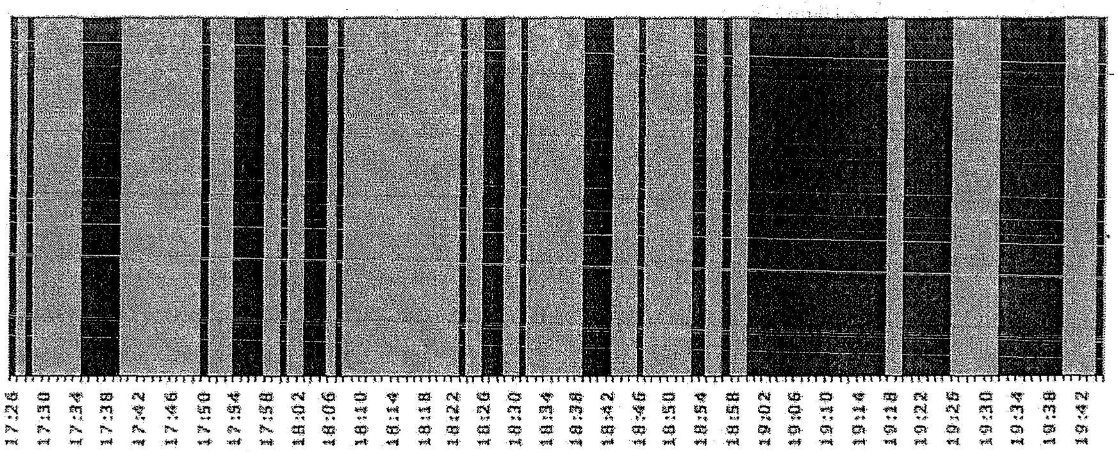

Figure 3. Duration of humvee stops during the traverse (black areas represent when humvee is not moving; narrow lines are 1 minute or less; stops separated by motion for a few seconds are represented as one stop)

Table 2 summarizes the nine stops (29 min.) when B and G discuss their location and route. Another location discussion that occurred when the humvee was not stopped (17:56) is included (however, as B is driving during the 17:56 discussion, primarily G is speaking and B does not make references to the map). Note that the noise in the humvee precluded normal conversation and would explain the need to stop if joint decision making were preferred or required by the task.

B and G each initiated five of the ten location/route discussions. During these discussions B (pilot) starts by referring to the route in the world (ROUTE IN WORLD, 3 times) or the map location of the humvee (WORLD=>MAP, twice). G (navigator) mentions the relation of the map to the world (once), the route in the world (twice) and map location (twice). Neither starts by referring to the route on the map (ROUTE ON MAP) or how a feature on the map corresponds to the world (MAP=>WORLD).

The first stop after leaving camp (17:50) involved a representational coordination that never occurred again, namely identifying in the aerial photos features and waypoints that were established when planning the route using the topographic map. This passage serves as a good introduction to the transcript analysis. Referring to Table 3, note for example that the statement "we're down here" while pointing on the map is classified as "World=>Map." The place labeled Marine Peak on the topographic map is related to the ~~aerial map, then from the aerial map is located in the world ("behind us"). Four of the 11~~ identified topics in this passage are "Topo=>Map," but this topic does not occur during any subsequent conversation on that day. Indeed, we can identify four distinct phases during the traverse:

1. 17:00-17:50—Materials organization and route planning and navigation procedures.
2. 17:50-17:54—Orientation of maps and photos to each other and the world.
3. 17:54-19:11—Navigating to the waypoints through the terrain.
4. 19:11-19:44—Coordinating local route with scouts.

The quantitative analysis of navigation discourse considers only phase three.

Table 2. Summary of passages when B and G discuss the navigation, indicating start time, duration, who initiated the discussion, the main topic in parentheses, and an illustrative statement. Except for 17:56, B stopped the humvee at each point.

TIME	DUR	NAVIGATION MOTIVE
17:50	1	G (Map=>World relation): "...get a sense of the topography of these things." *(omitted from quantitative analysis)*
17:54	4	B (Route in World): "Is there another entrance into that valley?"
17:56	4	B (route in world): "Which side do you recommend, G, that we go down this side...?" *(Not stopped, but included in analysis)*
18:00	< 1	G (Route in World): "...go to the right there..."
18:03	3	G (location: World=>Map): "Just check where we are."
18:23	1	B (location: World=>Map): "We're down here."
18:28	1	G (location: World=>Map): "I think this is this down here."
18:39	1	B (location: World=>Map): "You need to know exactly where we are"
18:53	2	G (location: World=>Map): "We should stop for a minute and figure out where we are"
19:00	11	B (location: Map=>World): "Does this make sense? Is that the valley down there?"

Table 4 provides a complete transcript of one of the longer stops, illustrating a typical interaction and how the conversation is segmented. Notice that B and G take turns speaking (speaker exchange; i.e., B row is followed by a G row and vice versa), but sometimes will speak about multiple topics during a turn (topic exchange; i.e., a G row follows a G row or a B row follows a B row). Procedural segments occur usually at the start or end of a discussion and are skipped over for purposes of analyzing the navigation process. Notice that without the gesture information it is impossible to know what B and G are referring to, as the words "this," "that," "here," and "there" are all used to refer to both features in the world and on the map.

Table 3. A unique discussion relating topographic map to the aerial photos and world features (17:50, duration 1 min). B's statements are in parentheses. Gestures are indicated by bracketed references. Other statements are uttered by G. MAP refers to an aerial photo; TOPO refers to a topographic map. Bold font indicates the main topic of the segment of the dialogue appearing in a given row, classified by Operation. Actor indicates who initiated this operation.

STATEMENTS	ACTOR	OPERATION
(Sorry say again)... Get a sense of topography on these things. **This is Marine Peak** <pointing on map with pencil> (right)	G	TOPO=>MAP
and **we're just heading**...I think down here <pointing out front window, then onto map>... maybe not..	G	ROUTE ON MAP
Marine Peak is behind us...	G	MAP=>WORLD
(right, so **these are** the two... <pointing on map>)	B	TOPO=>MAP
(**that's the Anderson Pass thing** <pointing on map>) yeah	B	TOPO=>MAP
(and **we just came** down on the back slope,)	B	ROUTE ON MAP
(so **what' we're seeing is this** <pointing on map>...) I think and...	B	WORLD=>MAP
(and so **the yellow brick valley** actually was before Marine Peak <pointing on map>, quite a bit before. Oh wait...)	B	TOPO=>MAP
(so, yeah because see, **we're down by here** now <pointing on map>) right	B	WORLD=>MAP
(so **we need to head**, that way <gesturing direction on map with pencil>) that way	B	ROUTE ON MAP
(so **why don't we go** back up <pointing out front window with left hand>, over the ridge?) Just hang a right...	B	ROUTE IN WORLD

Table 4. Navigation discussion between B and G during pause 18:03-18:06 (B's utterances are in parentheses); <gestures are indicated by brackets>.

Just hang on a second there, B... just check where we are, I think, **this hill is this one over here**?	G	WORLD -> MAP
(yeah, **this hill here is that dome**)	B	MAP -> WORLD
so we could just cut across I suppose (yes) if **we carry on this direction**, we could have them scout to the right here	G	ROUTE ON MAP
<pointing on map>		
over there <gesturing outside>	G	MAP -> WORLD
(But, we're supposed to make it to our waypoints,) okay (but at the same time...<G passes pencil to B, who takes map and looks at it, and proposes a way to modify waypoints>)		PROCEDURAL

(So **we're right here right** now, correct.) We're a little bit further on (really?) Yeah, I think we passed, that's the beginning of the valley, or at least up there. (yeah, okay)	B	WORLD=>MAP
And **we're looking out** that way <turning to front window>	G	MAP=>WORLD
(**we got that thing there** <looking on map>,)	B	WORLD=>MAP
(**this other hill <looks out left window> to the right**)	B	MAP=>WORLD
this material on the right here <looking out front window> looks a lot better ... (yeah <holding point on map with pencil>) and **I think if we just carry on straight ahead** (it's still not that way we want to go, it's that way <gesture outside?>) Well, it depends how far you...	G	ROUTE IN WORLD
(because **the map is oriented like this**, G.. so we're here <pointing on map>) right	B	WORLD=>MAP
(you see, there's the big dome there <referring to outside>, right?) yes (and there's a lower dome to right of it?) correct.	B	WORLD
(**that thing <outside> is that <on map>,** right?) yeah, yup.	B	WORLD=>MAP
Straight ahead? Well... drop down into that valley and... <gesturing out front window> (so we need to go around...)	G	ROUTE IN WORLD
(**you see that valley** <looking outside>?) Yeah (that we see disappearing in the distance,)	B	WORLD
(**that's what we want to follow**, right?)	B	ROUTE IN WORLD
(**isn't it that?** <pointing on map>) hang on.. (it's this. it's this here <pointing on map>) <looking out and back to map> yes, it's this bit here <pointing with pencil>	B	WORLD=>MAP
(yes, so **that's the direction we want to go**, right? <gesturing on map>) yup (to get up there)	B	ROUTE ON MAP
yes, I agree, so **just straight down this hill** <gesturing out window with pencil> (Over there...) towards **that valley** <both looking out window>	G	ROUTE IN WORLD
(and **could that possibly be even our high point over there**, in the great distance?) no, I think it's <referring to visible hill> this closer one <looks on map> ... (no, <points on map> the great distance.... **you see over there <looking out>, the great distance?** Is that our 1500 or 1150? <looking on map> which is where we're headed <G takes out another aerial map and aligns it on right with first map> Could be couldn't it?) <points on new map and looks out window> **Which one are you looking at? <both look outside> (the farthest point, the highest point you see on the horizon <pointing with left finger>) yup** <looking at map> (that could be) that could well be (our 1155) so if we're looking over towards this way, it'd be over to the right... might be (I think that makes sense, right?)	B	WORLD=>MAP

Well, we're almost directly.. If **we're looking down there <gesturing out window>, you're looking down this valley <gesturing on map> aren't you** (right) this <on map> seems further to the right (well, we could be looking down this <on map>)	G	WORLD=>MAP
(Anyway, we're headed down that way, is that correct?) yeah, we're headed down that way <gesturing outside>.	B	ROUTE IN WORLD

Figure 4 shows how pointing on the aerial photo typically occurs, using a finger and/or the red pencil, (which is exchanged at various points). Often B or G would hold a place fixed with a finger, while looking outside, then returning to the map to indicate a correspondence. Sometimes B picks up a photo to examine more closely, allowing it to be better illuminated by the light coming in his left window.

Figure 4. At time 18:06 G says, "You're looking down this valley" (on right, gesturing with finger and pencil; B on left). (Photo: W. Clancey/NASA Haughton Mars Project)

The last long, 11 minute navigation discussion at 19:00 (Table 5) reflects the group's concern with the topography ahead and uncertainty of what route to take. Near the start of the discussion B and G are almost exclusively relating the world and the map, with a route mentioned near the end. Figure 5 shows the view and corresponding map area of the "thick benches of snow" they use to confirm their location.

Figure 5. Photograph of view out humvee window (left); three snow patches in the upper center are believed to correspond to those in the aerial photo (right), indicated by G as he says, "I would put them, really, they should be up here; this is them here." Photo is annotated with a waypoint (1055) and the initial rough route plan. (Photos: W. Clancey/NASA Haughton Mars Project)

Table 5. Navigation discussion between B and G during 19:01-03

(you see) going off **to the left of this** <gesturing on map>, **is this** <gesturing outside>	G	MAP=>WORLD
(**do you see that it deepens?** Steepens, the walls? <just slightly looks out>) Yeah, I think it does, it's that down there <returning from look out right window> on the right (does it?) yeah (I can't see) yeah it does, yeah you can see it <pointing with pencil, looking out right window>, it's deep and that it, it's getting shallow. This is the shallow bit.	B	MAP=>WORLD
You see that snow bank? (yup) that thin strip of snow <returns to point to map> (yeah) **i think this** <referring to snow bank> **may be down here** <pointing on map>	G	WORLD=>MAP
(okay what about these, ah, <pointing with left hand out window to right> these three, these thick snow benches there, in that little tributary? <referring to what's visible outside> **where is that?**) Is it this? <pointing on map> Just running down into here...**Isn't that** <referring to tributary> **down there?** <pointing on map>	B	WORLD=>MAP
(okay... **and these guys?** <on map>) these guys are up here <referring to outside> (that's that?) yup, correct	B	MAP=>WORLD
~~(the snow I mean, the thick benches of snow right across)~~		
right across there? <referring to outside> uhm (... **is it that?** <pointing on map>) I would put them, really, they should be up here <pointing on map>, this is them here. (oh, yeah)	B	WORLD=>MAP
this river here <on map>, coming off, I'm pretty sure, **that's this here.** <pointing out window>	G	MAP=>WORLD

We're sitting on top of here <on map>, I think up here. (Really, up there?) no, uh, further forward I think (let's see, let me see <takes the maps and examines in the bright left light> ... yeah, I agree.)	G	WORLD=>MAP
(But actually I think that these, these thick snow banks are those, **the thick ones we see, are here** <pointing on map>, G) uh hunh	B	WORLD=>MAP
(cause **we're right there**) <looks out right window>	B	WORLD=>MAP
(the thick snow banks are these... <on map>)	B	WORLD=>MAP
(and **this intersection** <on map> **is that** <points with pencil out front window>) down here <looking out right window>. (oh, I see what you mean... yeah that intersection is that, yeah, yes, you're right, you're right)	B	MAP=>WORLD
so **those** <snow banks on map> **are them** <the thick snow banks outside> (okay)	G	WORLD=>MAP
so I think what we want to do is carry on down there <referring to outside>, **we'll be wanting to go in that direction** <looking out and down> (you want to head down there?) right,	G	ROUTE IN WORLD
in fact that point <gesturing out front right>, in the distance, may even be (our landmark, right?)	G	WORLD=>MAP
if you put that under here, we're actually not that far off (no) that's there, that maps onto there <lining up the maps>, so **we're looking out,** that way <gesturing direction on map>	G	WORLD -> MAP
(if we follow this valley <on map>)	B	ROUTE ON MAP
and that dome in the distance <referring to what's outside> (right) the top of that may very well be (right) our 1055	G	WORLD -> MAP

The identification of the snow banks is important for orienting the map. This localization method is difficult because there are many snow banks, and from a distance they are flattened and appear similar. The method is also amazing because it depends on the permanence and relative persistence of shapes of the snow banks over four decades. In fact, the area is generally snow-covered from September through May at least, so it is no coincidence that the photos would be taken during the height of summer when the most features are visible, which is when this humvee traverse occurred.

The subsequent exchange is very different, as the discussion shifts from locating the humvee to planning a route (Table 6). This sequence provides basic information about how route decisions were made (analyzed in the next section).

Table 6. Navigation discussion between B and G during 19:04-08

(so you see, by following **this valley** <gesturing on map>, we head straight towards it)	B	ROUTE ON MAP
yeah, and the question is whether we want to just uhm ... cut across there <referring to map>	G	ROUTE ON MAP
Do you want to go to **this waypoint?** (to this	G	ROUTE ON MAP

point? <pointing on map>) yeah. (well, to some degree, do we need to?) no, I think we could follow a ridge through here <gesturing on map with finger>		
(alright... cause we need to connect with our path here <pointing to thin line on right map>, right?) yeah, that's correct (so why don't we even cut across... straight that way?)	B	ROUTE ON MAP
well, it's looking pretty steep and horrible <referring to outside>, I would tend to go more to the left. I would avoid that valley down there (yeah, the lower banks have, have seem to be sort of less rocky, you know?)	G	ROUTE IN WORLD
yeah, I would go towards, do you see where that **first snow bank** is <pointing out right window> (which one?) << open window>> first one to the left <pointing> (right, the big thick one?) yeah, (okay)	G	WORLD
if we head down there <points outside throughout this description>, and then turn up **over the top,** around the snow banks, not straight across but go around (yup) and over the top,	G	ROUTE IN WORLD
I think if we carry on to the top, we'll connect up with here <points on map> (we have to look out for **this valley** here <pointing on map>, right>?) correct	G	ROUTE ON MAP
(so since we're here <on map>, suggesting we go up around those <on map>... actually we're beyond this map, let's get rid of this, we're completely on this map.... since we're here <on map>, these are your, oh, no, these are **your things** <referring to snowbanks>, right?) yeah	B	WORLD -> MAP
(so you're suggesting basically, we go down here <gesturing direction on map>, up and around **these guys**) yes and connect into here <looking on map and then outside>	B	ROUTE ON MAP
if we can find a way down this **pile of shart**. It looks pretty steep.... maybe one of these scouts wants to find a route down... I think once we get to the bottom there, it will be much easier to just go up to the top around.. (you know, I suspect that the other side is going to be exactly like this) the other side of what (i mean) that (one of **these hills**) I mean, we don't have a choice do we? I mean, this is no better than this (no, I agree) we're better cut the route shorter (...valley route that we can take, an alternative, hold on one second) <<< can hear wind, I ask for window to go up)>>>	G	ROUTE IN WORLD
(<looking out right window> Yeah, that <on map> is that <outside>, okay, I'm convinced)	B	MAP -> WORLD
we need to get down (right) into there	G	ROUTE IN

		WORLD
(right and what's behind <outside?> is that <on map?>, okay... can even recognize **the snow patches.**)	B	WORLD -> MAP
(So being here <pointing on map> and wanting to be there <on map>) yup. I think our first objective is to get down into **that valley** and to get behind **those snow patches** there <pointing on map> (right right..to get there) once we get there... we can stop again, well you can stop further, well, we might stop before then, at least we want to stop there and figure out how to connect up with **this bit** <referring to thin line on map beyond next waypoint> (yup, very good) as soon as we do that... we'll be...almost getting onto this map...we're well on our way then (yup) heading into...	B	ROUTE ON MAP

At this point (immediately after G's last remark in Table 6), B says "Very good, let's GPS this place.. let's call it decision point...," which G specifies, "...way point B."

B then says, "Okay robotic scouts, we need to go across this valley and up the other side, and get around to those thick snow benches that we see on our right, that series of big ones? And to get up and behind those." B and the scouts then discuss further how they should proceed. One comments that "we're really doing well...we'll be there by midnight."

After a seven minute rest break, the distant scout tells the humvee driver, to follow the ATV nearby, in front of the humvee. B comments, "Okay, follow <near scout, S1>. Now, this is a very important piece of information... incredibly important." G says, "What?" The observer asks, "Do we believe it?" G responds, "Yes, it is, incredibly important. The future of this vehicle rests on this correct decision."

B tells G, "Call S1." G radios: "S1, can you hear?" Someone says, "Are we following you, S1?" B asks, "Who am I following? S1?" G asks, "S1, are we following you?" B stops the engine and say, "I'm going to have a look guys." The observer and G then comment about dinner and the possibility of a breakdown; G says, "I hope this thing makes it there and back...we've not really come up with a contingency plan...." The observer says, "This is just slightly worse than the section where I said you wouldn't drive on anything worse than this." G says, "I think when the boulders get as large as the tracks then you start to have a problem...."

So it is clear at this point, 20 minutes before the mechanical problem, that the terrain is not good, and the scout's judgment requires confirmation. During the next 15 minutes the scouts continue to look for a good route into the valley, while B goes out to examine the situation. G and the observer discuss the limitations of robots and other options for finding routes. G shows how the aerial photo and terrain correspond (Figure

5) and comments, "Now if we were on Mars you could never tell that's a rough piece of land. It's just impossible to know... another terrace there... Houston, we have a problem..." A few minutes later, B returns and G asks him, "What do you reckon?" "Should be able to make it." G says," ... go over the top." B replies, "We're going to go other there, where it's smooth." Soon after some rocks became caught in the humvee's tracks and the group was stopped for the night.

NAVIGATION DIALOGUE ANALYSIS

The navigation discussions were analyzed for patterns in how topics were related sequentially and correlations between topics and the speaker. The overall impression one has on reading the transcript is that during navigation discussions B, the driver, is focusing on the map both to locate the humvee and gleam information about routes, while G is focusing on the character of the landscape and finding a route in the world. Can we show this quantitatively by analyzing the structure of the conversations?

Table 7 shows every transition that occurs and is the basis of subsequent tables and figures that represent patterns. For example, the first two segments in Table 4 are represented in Table 7 by "GB" in row labeled World=>Map and the column labeled Map=>World (i.e., the dialogue transitions *from* G mentioning World=>Map *to* B mentioning Map=>World). The entry "2BG, 3BB, GB, 2GG" indicates that the GB relation only occurred once in the dialogs; however, the transition occurs seven other times, including three times when B mentioned World=>Map and immediately after mentioned Map=>World.

Table 7. Sequential topic transitions during navigation discussions (Table 2). Cells indicate speakers (e.g., B speaking about Map=>World was twice followed by G speaking about World=>Map; hence 2BG appears in row 1, column 2). Bold font indicates a dominant transition as defined in the text.

TO FROM	MAP => WORLD	WORLD => MAP	ROUTE ON MAP	ROUTE IN WORLD
MAP => WORLD	GB	2BG,2BB GB,2GG	BG GG	2BG GB
WORLD => MAP	2BG,3BB GB,2GG	BG,**3BB** 2GB,2GG	BG,**5BB** 2GB,GG	BG,BB GB,**3GG**
ROUTE ON MAP	BG **3GG**	2BG GB, **2GG**	BG GB,GG	**3BG**,BB GG
ROUTE IN WORLD	**2GB**	2BB **3GB**,GG	BG **2GG**	GB,GG

The bold font in Table 7 designates a *dominant turn-taking transition*. For this purpose, BG and BB are viewed as a pair, and GB and GG are a pair. For each pair, we want to know if one appears much more frequently (e.g., does GB appear much more frequently than GG?). As defined here, for a transition (e.g., GB) to be dominant, its partner must be missing (e.g., GG is missing in last row, column 2) or the ratio must be at least 3 to 1 (e.g., 3BG is dominant over BB in "Route on Map To Route in World").

Table 8 aggregates all 16 possible transitions as percentages (16 cells add to 100%). The least frequent transition was for anyone to follow a remark about how the map related to the world by another remark of that kind (1.4%), as Table 8 showed it occurred only once in the 74 topic transitions. In contrast, identifying a world feature in the map (World=>Map) was much more frequently followed by the same kind of remark (10.8%). ~~Table 8 shows us that each of the four combinations occurred (BG, BB, GB,~~ GG), but B was somewhat more likely to make two such observations in sequence (BG vs. 3BB). The most common transition (12.2%), World=>Map followed by a remark about the route on the map, is logical because attention has shifted to the map at this point.

Table 9 counts how often the possible transitions[‡‡] (BG, BB, GB, GG) occur by summing across Table 7. The TOTAL row shows that alternation of the speakers was fairly even, though G was somewhat more likely to two location or navigation remarks in sequence (GG = 22/74). Most obviously, B is focused somewhat more on the aerial photo (map), as 71% of his repeated remarks (BB) are World=>Map and 72% of his remarks overall (49% + 23%) focus on or into the map. In contrast, 59% of G's remarks focus on the map. B appears to be "thinking in" the map, while G is more concerned (26% vs. 9% for B) with a route in the world (his role as navigator). B focuses somewhat more than G on identifying world features in the map (World=>Map, 49% vs. 36%). B appears more concerned with locating the Humvee, while G brings the topic back to the route.

Table 8. Percentage of transitions that occur from topic category designated in row header to the category in the column (e.g., World=>Map followed by Route on Map is most common, 12.2%).

TO / FROM	MAP => WORLD	WORLD => MAP	ROUTE ON MAP	ROUTE IN WORLD
MAP => WORLD	1.4%	9.5%	2.7%	4.1%
WORLD => MAP	10.8%	10.8%	12.2%	8.1%
ROUTE ON MAP	5.4%	6.8%	4.1%	6.8%
ROUTE IN WORLD	2.7%	8.1%	4.1%	2.7%

[‡‡] We use the terms topic, segment, and utterance interchangeably to refer to one of the classified sections of the transcript, i.e., a row in Tables 4, 5, or 6. A "transition" is a sequence of two topics and a speaker pair, e.g., "Route on Map -> World=>Map" corresponds to the last two rows of Table 5 and is designated BG.

Table 9. For a given starting topic, percentage (and number) of transitions of each type (e.g., when B spoke about World=>Map, G spoke next 5 times [BG], and B spoke next 12 times [BB]). Total columns indicate how often each person mentioned a topic (e.g., B mentioned World=>Map 17 times = 49% of his 35 utterances) and sum to 100%. Last column totals the 74 classified segments in the transcripts (i.e., 74 topics) with the totals shown (e.g., World=>Map occurs 31 times). In each row, BG+BB = GB+GG = 100%.

	SPEAKER SEQUENCE				TOTAL		
FROM TOPIC	BG	BB	GB	GG	B	G	TOTAL
MAP => WORLD	**71%** (5)	29% (2)	50% (3)	50% (3)	20% (7)	15% (6)	18% (13)
WORLD => MAP	29% (5)	**71%** (12)	43% (6)	57% (8)	49% (17)	36% (14)	42% (31)
ROUTE ON MAP	**88%** (7)	13% (1)	22% (2)	**78%** (7)	23% (8)	23% (9)	23% (17)
ROUTE IN WORLD	33% (1)	67% (2)	**60%** (6)	40% (4)	9% (3)	26% (10)	18% (13)
TOTAL	18	17	17	22	35	39	100% (74)

To highlight dominant transitions, percentages in Table 9 are in bold font when the speaker's frequency of mentioning that topic is >=20% (e.g., B utters Map=>World 7 times = 20% of his 35 utterances) and the frequency for the sequence is >=60%. Thus, BG is highlighted for Map=>World, showing that in this event (i.e., when B utters Map=>World), G is much more likely to speak next. Similarly, when B utters World=>Map, he is much more likely to speak again. In contrast, when either B or G mention "Route on Map," G speaks next. Finally, when G mentions "Route in World," B speaks next.

Table 10 aggregates Table 7 transitions according to topic (each row adds to 100%). For example, Map=>World most often (54%) transitions to (i.e., is followed by) World=>Map and relatively infrequently transitions to itself (8%).

Table 11 shows focus shifts aggregated over all topic segments. For this purpose, the focus of "Route in World" and "Map=>World" is World, and the focus of "Route on Map" and "World=>Map" is Map. Thus the transition from Map=>World to Route on Map is classified as "From World to Map." The table reveals that *65% of the topics were focusing in the map* (sum of MAP row) *and 35% were focusing on the world.* Referring to Table 9 TOTAL column, we observe that *60% of remarks concerned locating the humvee (World⇔ Map), while 40% concerned the route.*

Table 10. Percentage of transitions that occur within a category, combining speakers (each row adds to 100%). For example, Map=>World transitions to World=>Map with frequency of 54%.

TO FROM	MAP => WORLD	WORLD => MAP	ROUTE ON MAP	ROUTE IN WORLD
MAP => WORLD	8%	54%	15%	23%
WORLD => MAP	26%	26%	29%	19%
ROUTE ON MAP	24%	29%	18%	29%
ROUTE IN WORLD	15%	46%	23%	15%

Table 11. Frequency of focus shifts, independent of speaker (total = 100%).

TO FROM	WORLD	MAP
WORLD	11%	24%
MAP	31%	34%

Many high frequency patterns can be found, but to narrow the analysis, we list the invariants and missing events (Table 12).

Table 12. Invariant turn-taking patterns and possible interpretations (cf. Table 7)

Turn-Taking Pattern	Interpretation/Restatement
When Map=>World and Route in World are mentioned in either order, the speakers alternate turns.	Focusing on the world, the speakers take turns relating map features and articulating the route.
When Map=>World and Route on Map are mentioned in either order, G is always the second speaker.	G alone moves the topic between a map route and identifying a map feature in the world.
Only G mentions Route on Map sequentially.	B never follows his map route by another map route remark.
~~3GG but not BB: Route On Map –~~ Map=>World	~~B never follows his map route by a~~ world⇔map relation.
2GG but not BB: Route On Map – World=>Map	
After B mentions Route on Map, if he speaks again (20%) he only mentions Route in World.	B's remarks about the map route are often posed as questions, which G answers by identifying map features or continuing with the map route.

3BG but not GB: Route on Map – Route in World	B never follows G's map route by a world route.
After B focuses on the world, and the world is the next focus, G is always speaking.	B never makes two sequential references to the world. He instead returns focus to the map when he speaks again.
2GG but not BB: Route In World – Route On Map	B never follows his world route by a map route.
2GB but not BG: Route in World – Map=>World	G never follows B's world route by a world⇔map relation.
3GB but not BG: Route in World – World=>Map	
After B mentions Map=>World or Route in World, neither mention that topic next. After B mentions Route in World, neither mention Map=>World next.	After B focuses in the world, they either focus on the map or shift between route and feature.
After B or G focuses in the world, only G mentions Route on Map next.	In bringing focus back to the map, G always states the route, not feature relations.

Regarding the overall turn-taking, the overall dialogue has about as many BG transitions (18, Table 9) as GB (17). Thus, G is somewhat more likely to speak (40/74 = 54%) because he speaks more often in sequence (22 vs. 17). This may occur because B is asking G questions (see Table 5).

Also, *G is more actively shifting the topic between the map and the world:* After G focuses on the map and the world is the next focus, G is speaking again (9/11 =82%). The inverse is not true—after B focuses on the map and the topic shifts to the world, he is less frequently the speaker (5/12 = 42%).

Regarding topic, after any statement focusing in the *world* (Map=>World or Route in World), the next statement is more frequently (18/26= 69%) focused in the *map*. (But the converse is not true: after focusing on the map, the next focus is split, 23 vs. 25). In particular, after B focuses in the world, the next focus is almost always on the map (8/10 = 80%; for G the relation is only 50-50).

Figure 6 shows the dominant transitions of topic and speaker. A focus in the world (left side of diagram, Map=>World or Route in World) most often leads to either speaker identifying a world feature on the map (World=>Map, Table 10; also 50% of next topic, 13/26 transitions), which is overall the most common utterance (Table 9, 42%) and constitutes nearly half of B's utterances (Table 9, column B, 49%). This is followed somewhat most often by Route on Map (Table 10, 29%), uttered by B (Figure 6, caption), followed by a return to World=>Map (29%)—and whatever is said, it is most often stated by G (Table 9, columns BG + GG = 14/17 = 82%). Notice also that World=>Map is repeated more than twice as often as any other topic (10.8% of all transitions, Table 8, diagonal) and most of the time by sequential utterances (Table 9, BB + GG =20/31 = 66%).

To determine the significance of the data, a Davison-Hinkley Chi-Square test was performed for each table[§§]. The significance levels (Table 13) indicate that only the data in Table 11 data (topic shifts) are likely to be true (i.e., not due to chance; significance ~~level is less than .05). As is common in conversation analysis of unique situations, 1.5~~ hours of data are not sufficient to establish statistical significance of the patterns that appear to be meaningful.

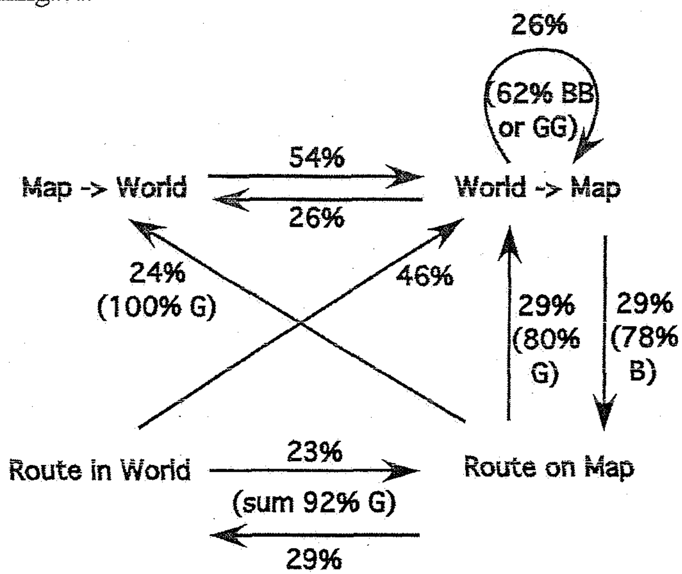

Figure 6. Strong correlations in topic transitions. Percentages along arrows are from Table 10 (54% of the Map->World remarks transition to World->Map vs. 46% of the Route in World remarks). (Percents in parentheses designate dominant speaker for that transition, from Table 9. E.g., B is dominant in transitions from World=>Map to the Route on Map (9 transitions = [2GB + 5BB => 7/9 = 78%] + [BG + GG = 12%]).

Table 13. Statistical analysis of primary data tables. Chi-Square and Significance Level are based on Davison-Hinkley method applied to one copy of the data. Strength indicates how many times the data would need to be replicated for significance level <= .05.

Table	Chi-Square	Sig Level	Strength
7	64.23	0.43	2
8	19.19	0.59	2
9	14.53	0.69	3
11	7.88	0.001	1

§§ Calculations using Davison-Hinkley method are based on Example 4.22, pp. 177 ff, and Algorithm 9.1 (balanced bootstrap) pp. 439 ff and Problem 2, p. 488.

However, what if the same data were observed again? Using the "boot-strap method,"[17] we calculate the "strength" number (i.e., how many copies of the data, the sequence of 74 topic transitions, that would be required to reach a significant level). We assume that the analysis should be discounted when this number is five or more. One (just the original data) means significant, and two means the data would be significant if we observed a second data set like the first. This method indicates that the data in Table 9, which attempts to locate speaker-specific patterns, is more likely to be due to chance.

The patterns aside, one can consider the logic of the various transitions. The shift between Map=>World to World=>Map is a natural back and forth process of looking for a map feature in the world and trying to identify a world feature in the map. Locating the humvee in the map (World=>Map) is a requirement for establishing a route on the map, which then naturally needs to be found in the world (Route in World). Indeed, locating the humvee in the map and establishing a route in the world are the only two requirements of the navigation task (accounting for all of the navigation stops except the first orientation, Table 2), with relating map and world features only being a means to these ends. Of these, relating the world to the map (what is that?) proceeds from a visible feature (e.g., a valley, dome, or snow bank), which serves a kind of clue for locating the humvee. In contrast, relating a feature on the map to the world is a kind of academic exercise, and it is striking that, except for the waypoints, the features identified at first on the topographic map were completely ignored later. Thus 34% of all statements relate world to map, more than twice as many as Map=>World.

Of all the topic relations, the transition from Route in World to Map=>World is perhaps least logical, because it implies a shift from talking about the landscape to relating a feature in the map to the landscape. This explains why speaker exchange occurs when focusing on the world (i.e., while one speaker looks at the world, the other uses the opportunity to mention a map feature previously held in mind or perhaps under his finger). Neither B nor G mention Route in World and Map=>World in sequence (i.e., GG and BB are missing in these two cells in Table 9). The only other sequence of topics that G omits is repeating Map=>World.

Notice that many more issues might have been considered in this analysis, such as the proportion of questions to assertions, the exchange of the pencil, the methods of establishing a common focus in the world or on the map, and the coordination with the scouts.

EVALUATION OF OUTCOME HYPOTHESES

Here we abstract from the data to characterize the navigation dialogues more broadly and evaluate the navigation-related hypotheses stated earlier. We begin by considering some basic questions about the navigation process:

- *What percentage and amount of time was devoted to locating the humvee?* 60% of the utterances concern the location of the humvee (World⇔Map relations), accounting for roughly 18 min (.6 x 29 min, Table 2) or > 25% of the paused time (Table 1).

- *Were the calls to stop to locate the humvee or to choose the route?* The last six of the nine stops, occurring during the last hour, were to locate the humvee (e.g., at 18:39, B says, "G, you need to know exactly where we are... sometimes we need to stop for maybe 5 minutes..."), which provided information required for route finding.
- *How were decisions made about location and route?* B and G each called for a location stop and map check three times during the last hour. B appears to be assisting by locating the humvee in the map (World=>Map); G connects the projected map route to the world. B's contributions to the navigation are a subset of G's, fitting G's role as navigator and B's driving responsibility.
- *How do they work? Who initiates what?* B worries more about location and G worries more about route. Accordingly, each becomes more engaged (more likely to speak again), after their primary interest is mentioned.
- *Are they explaining and justifying individual conclusions or solving problems together?* During the two hours analyzed here, G is able to look at the maps and relate them to the world during the hour that B is driving the vehicle, so he naturally has more observations and thoughts to convey about the route and world-map relationships.B almost always presents location relations and routes as questions, thus prompting G (this discourse pattern is called *mitigation*[18]), the navigator, to make assertions. (For example, when G says, "What we need to do is just pick out a route," B replies, "Does it make us go over this high point, or? no?").
- *Are all of the questions and statements necessary for the task?* The dialogue is sharply focused on location and navigation, except for the interlude before the final stop, outlined earlier, when the uncertain route raised broader issues.
- *Who stated the route first?* Of 30 route remarks, B states 11 and G states 19.
- *Could decisions have been made without stopping?* Apparently not. The stops indicate that the humvee is moving too fast (< 10 km/hr!) for the navigator to follow the location on the map. Thus, if they didn't stop they would become lost. Also, the engine noise made it difficult to talk, and clearly the pilot contributes to identifying the location on the map (his primary focus).
- *Does the navigator require help or just prefer to do the job together?* The navigator needs some kind of assistance, but stopping was due to losing track of the current location on the map, not because of needing the pilot's help.
- *Were the scouts helping?* The scouts role was to assist in route finding, but their paths complicated the location problem as they chose paths amenable to riding on an ATV.

At this point, we can directly address the hypotheses stated earlier about navigation-related problems that prevented the humvee crew from reaching the coast:

- *Aerial photographs were insufficient for navigation:* Evidently true—locating the humvee caused significant overhead, including forced stops, and distracted the navigator from working with the scouts to plan routes.

- *Route needed to be planned more globally:* True—local obstacles for the scouts were leading to unplanned detours, which introduced uncertainty in the overall route and made continuous replanning necessary. 45 min were spent finding a local route into a valley, which then caused a mechanical failure. Such terrain must be detected and avoided well in advance (preferably before the trip leaves base camp).

- *Scouts didn't provide needed local obstacle and route information:* True—the crew learned that a rocky hillside affects an ATV and a humvee on tracks differently. The ATVs could not move sufficiently quickly to try different routes in advance of the humvee; the drivers were also impaired by rain and inadequate communications. The navigator was too busy locating the humvee to direct the scouts more appropriately. The scouts were not benefiting from the aerial photos at all; their lack of shared orientation is evident when they come together to talk (Figure 7).

Figure 7. G (middle) relates his map understanding to the scouts' conflicting sense of direction. (Photo: W. Clancey/NASA Haughton Mars Project)

CONCLUSIONS

The humvee traverse to the north coast of Devon Island provided an excellent authentic, yet experimental setting for studying how people navigate in unfamiliar terrain. The data show many intriguing patterns, which suggest that the pilot was interested to use the map (aerial photo) for locating the humvee and finding a route, while the co-pilot's interest reflected his role of finding a route in the world. The study relates to previous work that shows the inseparability of gesture and speech in such dialogs, as well as the regularity of conversational turn-taking. The patterns revealed here could be applied directly for constructing a computer system that could use other sources of information (such as GPS and other maps) to naturally contribute to the human dialogue, in the manner of CapCom. More work is required to separate individual preferences in this particular crew from more generally shared patterns of narrative and reasoning (e.g., what would happen if B and G swapped roles?).

The experiment demonstrated clearly the importance of having sufficient tools to locate the vehicle and to plan routes globally, avoiding terrain that will imperil the vehicle and its crew or cause long detours. Automatically locating the humvee on a map shared by the scouts would allow the navigator to spend more time looking ahead to plan routes and get relevant information from the scouts (e.g., by having them test particular paths).

GPS would solve the location problem, but of course could not in itself generate a route plan. Some other method must be invented to find a route in advance, with robots or scout vehicles, perhaps using satellite or aerial photos to detect problematic terrain. Note that as the mechanical problem revealed, the issue is not merely finding a sufficiently level path, but identifying surfaces that are difficult or risky for the vehicle being used (e.g., consider how Opportunity was stuck on Meridiani Planum for a month in 2005). Impassable routes might be color-coded or shaded, just as Mars Exploration Rover planners marked out hillside areas where the sun's angle would prevent the solar cells from sufficiently recharging the batteries.

The planned route might be superimposed on aerial and/or topographic maps, and depicted as 3-d fly-through visualizations. The need to stop periodically to reflect on the quality of the route is certainly not precluded, and might be combined with rock and mineral sampling, deploying instruments, or resting. The difficulty of relating aerial and local perspectives is obvious in the navigation dialogues, and was mentioned by Cernan in his journal about Apollo 17:

> When I was near Nansen, I wanted to be sure in my mind what was to the north and what was back to the east, even if I couldn't see very far in those directions from the ground. I wanted to have a feel for where I was; not from a navigation point of view but from a geographic point of view. And then I wanted to understand the topography, which you can't fully appreciate until you literally get down to the surface. From orbit, Tracy's Rock (at Station 6) doesn't mean anything; but, when you get down in there, you can appreciate the slopes and the sizes of the boulders and the craters.

Following the Apollo CapCom model, rather than limiting conversations back to base camp by design, why not rely on someone there to help the crew? An aerial balloon or high-resolution satellite images might have been used by an assistant back at camp or even on Earth, comparing with photos sent back from the humvee to confirm and replan routes.

The difficulty of communicating with the scouts demonstrates that considerable thought must be devoted to designing robots that would perform a similar task. First, teleoperation from the vehicle would require at least a third crew member, which is plausible. A good follow-up experiment might involve having a third person in the humvee mediate the work of the scouts by continuous communication with them on a voice loop. The scout interactions shows that their actions must be more restricted to certain kinds of actions and follow defined protocols, to provide useful information for design of robotic scouts. This in turn requires considering more carefully what kind of information is desired and how it should be conveyed. For example, the distant scout might be tasked with only *confirming* a globally planned route, whose path would be visible on a display to the crew and known by the scout (whether a person or robot).

How might a computer agent have helped the crew? Notice that the navigator and pilot are coordinating the routes of the two scouts, the proximal path of the humvee, and the global route of the humvee. Add to this work the need perhaps to periodically manage the humvee's transport and life-support systems, and to intervene to teleoperate a stuck robot (18:46—"Uh oh, our robot's broken... how you doing <S1>?). Aside from basic location tracking and automating reports back to the support crew at base camp, an agent might providing basic caution and warning to the vehicle crew about systems and the state of the robots. In designing such agents, the present experiment shows the value of well-defined protocols, even in such real-life situations, so particular methods can be tested. In this respect, the operational test was a success, as the experiment established that the navigation method was inadequate for the task: In such terrain with such a vehicle, efficient, reliable navigation requires an automated positioning system and detailed planning on maps with better than 1 m resolution.

As we believe the experiment and analysis shows, we are ready to go back to Devon Island and try again with different equipment and new procedures. Surely this is the advantage of an analog site in preparing for planetary expeditions: The chance to try and try again, so when we go to Mars, we will know what to build and how to prepare.

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