Learning to navigate

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The navigation activity

At all times while a naval vessel is underway, a plot of its past and projected movements is maintained. Day and night, whenever a ship is neither tied to a pier nor at anchor, navigation computations are performed. In a long passage, the navigation activities may be continuously performed for weeks or even months on end. Most of the time the work of navigation is performed by one person working alone, but when a ship leaves or enters port, or operates in any other environment where maneuverability is restricted, the computational requirements of the task may exceed the capabilities of any individual. In such circumstances, the navigation duties are carried out by a team of individuals working together.

The work described here is a continuation of my long-standing interest at looking at cognition in the real world. In earlier work on litigation in the Trobriand Islands (Hutchins, 1978, 1980), and on navigation without instruments in Micronesia (Hutchins, 1983; Hutchins & Hinton, 1984), I was mainly concerned with the influence of culture on the cognition of individual actors where their activities, while socially situated, were considered primarily as individual cognitive accomplishments. Looking at navigation as it is actually conducted aboard ships, however, brought home to me the extent to which cognitive accomplishments can be joint accomplishments, not attributable to any individual. Another absolutely apparent feature of this setting is the extent to which the computational accomplishments of navigation are mediated by a variety of tools and representational technologies.
Developmental arenas in navigation

The activity of ship navigation is continuously developing in several senses.

First, navigation as it is practiced today is part of a tradition that can be traced back more than two thousand years. Many of the star names used in modern navigation, for example, were used by Egyptian astronomers. When a modern navigator does celestial navigation, he is seeing a sky (at least the northern sky) composed of constellations that were grouped and identified by navigators in the Mediterranean thousands of years ago. Between the early attempts at measurement and map making and the present day, there lies a rich history of technological innovations. In a typical hour of navigation activity, a modern navigator may utilize technologies that range in age from a few years to many hundreds of years. The time scale of the development of navigation practice may be measured in centuries.

A second developmental line in the world of navigation unfolds in the careers of navigation practitioners. In the U.S. Navy, navigation is performed by sailors of the quartermaster rating. Quartermasters begin their careers with rather limited duties and advance to more complicated procedures as they gain expertise. The time scale of this aspect of development may be measured in years.

A third developmental aspect concerns the microgenesis of individual cognition in social interaction. Because people jointly perform the task of navigation, and do so with differing levels of expertise, much of the learning of navigation skills takes place in interaction. The time scale of this aspect of development may be measured in minutes.

The final sense in which the activity of navigation is to be understood as a developmental process involves a return to the first point: the microgenesis of the embedding culture in the conduct of the activity itself. While every navigator and every navigation team depend upon the long tradition that precedes them to structure their task environment, they also are part of the tradition for those who follow. The innovations that change the shape of the navigation activity come into being in the practice of navigation and their development can be studied in the microstructure of the interactions among people, tools, and task. We can see patterns of technological change over the long run, but we can also see the details of the process of innovation in the minutia of actual practice.

The principal focus of this chapter is the nature of the navigation activity as a context for thinking and learning. In particular I will try to show how certain aspects of the conduct of navigation work contribute to the development of the quartermasters' navigation expertise.

The navigation task setting

An important fact about this setting is that the primary function of a peacetime military is what is called "the maintenance of readiness." The military establishment is a big institution full of terrifying weapons systems and other artifacts. The glue that holds the artifacts together, which makes the separate ships and planes and missiles and bombs into something more than a collection of hardware, is human activity. But there are high rates of personnel turnover in the military. The human parts keep passing through the system, so that even though the system is ready to make war one day, it will not be ready the next unless the expertise of the people departing is continually replaced by newly acquired skills of those who have more recently entered. This high turnover of personnel and the resulting need for the continual manufacture of replacement expertise make the military a fertile ground for research into the nature of learning in cultural context. So, in some sense, my discussion concerns the microstructure of maintaining the readiness of the human component of the war machine.

The events described in this chapter took place aboard a ship called an amphibious helicopter transport. Its warfare mission is to transport marine troops across the seas and then deliver them to the battlefields in the 25 helicopters that are carried on board. The helicopters also bring troops back to the ship, which has a small hospital and a complete operating theater on board.

Ships of this class are often mistaken for true aircraft carriers of the sort that carry jet planes. As is the case with true aircraft carriers, the hull is capped by a large flat flight deck, which creates an overhang on all sides of the ship. But this flight deck is only 592 feet
long—just over half the length of a carrier deck and much too small to handle fixed-wing aircraft. About halfway between bow and stern, jutting up out of the smooth expanse of the flight deck on the starboard rail, stands a five-story structure called the island. The island occupies the rightmost 20 feet of the flight deck which is about 100 feet wide. Three levels above the flight deck in the island is the navigation bridge or “pilothouse” where most of the navigation work takes place. Also in the island are the air operations office from which the helicopters are controlled, and a flag bridge where an admiral and his staff can work. The top of the island bristles with radar antennae.

The ship extends 28 feet below the surface of the water and weighs 17,000 tons empty. It is pushed through the water by a single propeller driven by a 22,000-horsepower steam turbine engine. These properties of the ship are important to the navigation task because they describe a vehicle of very limited maneuverability. The normal crew compliment of the ship is 44 officers and 608 enlisted men. Because the ship is primarily a troop transport vessel, it also has accommodations for more than 2,000 troops.

The physical layout of the spaces in which navigation is practiced is shown in Figure 2.1. This is a plan view of the navigation bridge, which is in the island three levels above the flight deck. The bow of the ship is to the left. The heavy line indicates the skin of the ship, whereas medium-weight exterior lines indicate railings on exterior walkways and medium-weight interior lines indicate interior walls. The elliptical shapes are duty stations for the members of the navigation team.

The navigation computations

The central computations in navigation answer the questions, Where are we? and If we proceed in a certain way for a specified time, where will we be? Answering the first question is called “fixing the position” or “getting a fix.” Answering the second is called “dead reckoning.” It is necessary to answer the first in order to answer the second, and it is necessary to answer the second to keep the ship out of danger. This is especially true for large ships that lack maneuverability. In order to make a turn in restricted waters in a big ship, it is not good enough to know when one has reached the point where the ship is to make the turn. Because of the lag in maneuvering response of such a massive object, when a ship reaches the turn point, if it has not already taken action to make the turn, it is too late to do so.

Position fixing by visual bearings

The simplest form of position fixing, and the one that concerns us here, is position fixing by visual bearings. For this we need a chart of the region around the ship, and a way to measure the direction, say with respect to north, of the line of sight connecting the ship and some landmark on the shore. The direction of a landmark from the ship is called the landmark's bearing. Imagine the line of sight between the ship and a known landmark. Although we know that one end of the line is at the landmark and we know the direction of the line, we can't just draw the line on the chart that corresponds to the line of sight between ship and landmark because we don't know where the other end of the line is. The other end of the line is where the ship is and that is what we are trying to discover.

Suppose we draw a line on a chart starting at the location of the landmark on the chart and extend it past where we think the ship is, perhaps off the edge of the chart if we are really unsure. We still don't know just where the ship is, but we do know it must be
somewhere on that line. Such a line is called a “line of position.” If we have another line of position, constructed on the basis of the direction of the line of sight to another known landmark, then we know that the ship is also on that line. And if the ship is on both these lines at the same time, the only place it can be is where they intersect.

Each line of position thus provides a one-dimensional constraint on the position from which the landmark was observed. The intersection of two lines of position uniquely constrains the location from which the observations were made.

The nautical chart

This computation could be realized in terms of many types of representations. For example, the lines of position could be expressed as equations of lines in a coordinate space, and the location of the intersection of the lines could be computed analytically by solving the simultaneous equations of the two lines of position. That is in fact how the problem is represented in some navigation computers, but it is not the way it is most often done. In our tradition of navigation, the central representational and computational artifact is the navigation chart. The chart is a spatial analogy to the large-scale space surrounding the ship. Locations on the chart correspond to locations in large-scale space. On a chart, lines of position are represented as pencil lines, and the location of the intersection of lines of position is computed graphically by drawing the lines on the chart. Although any two intersecting lines of position will uniquely specify the position of the ship, in practice, three lines of position are normally obtained for a fix. The intersection of the three lines forms a small triangle. (See Figure 2.2 for an example of a position fix with an acceptably small triangle.) If all of the observations are accurate and the lines are carefully plotted, the triangle formed will be very small. A navigator’s anxiety is roughly proportional to the area of the fix triangle. Big triangles are bad. They mean that there is a problem somewhere in the processing of the information.

The computation of where we will be if we move in a particular direction at a particular speed for a specified time is also answered by geometric construction on a chart. A track line begins at a known position and is extended in the direction of travel. To compute a projected position at a particular time in the future, for example, one multiplies the ship’s speed by the time interval in question to get a prediction of the distance that will be traveled. This distance from the known starting point is then spanned on the track line to determine the predicted position. Figure 2.3 shows a dead reckoning track line extended from the fix.

From these two simple examples, it can be seen that a chart is much more like a coordinate space in analytic geometry than it is like the casual maps we draw to direct friends to our homes or offices.

Mercator projection charts are specially constructed computational artifacts that support this computation. In particular they are made so that angular relations among positions are preserved. The preservation of angular relationships is required if position is to be estab-
lished by visual lines of position. Other desirable chart properties are sacrificed on the Mercator projection in order to preserve the one property that makes this kind of navigation possible. Many people know that the relative size of areas on Mercator projection charts does not correspond to area in the world. Greenland appears as large as South America on some charts, despite the fact that the area of South America is many times that of Greenland. Mercator projection charts also lack a constant distance scale. Away from the equator, a displacement on the chart that represents 10 miles in the east-west orientation will represent a much shorter distance in the north-south orientation. This is not to say Mercator projection charts are accurate or not accurate, only that they are tuned for some kinds of navigation, and not for others.

It is difficult to overestimate the importance of the development and use of external representational media in this task. The contrast with navigation in nonliterate societies where it is carried out without the aid of external representations is striking. The task and its computational properties are determined in large part by the structure of the tools with which the navigators work.

The fix cycle

The necessity for continuously plotting the ship’s position, projecting the track, and preparing to plot the next position is satisfied by a cycle of activity called the “fix cycle.” As long as a ship is underway, it is continually executing this cycle. If it is away from land and other dangers, the cycle may be completed at a leisurely pace of, say, once every half hour. When the ship is in restricted waters, however, it may be necessary to complete the cycle on 1-minute intervals. Under these conditions, no single person could make all of the observations and do all of the computations required to complete the cycle in the amount of time available.

When the ship is operating in restricted waters, the work of the fix cycle is distributed across a team of six people. The duty stations of the members of the team in the configuration called Sea and Anchor Detail are shown in Figure 2.1 as ellipses. We can follow the fix cycle by following information through the system.

New information about the location of the ship comes from the bearing takers on the wings of the ship (positions 1 and 2 in Figure 2.1). They find landmarks on the shore in the vicinity of the ship and measure the bearings of the landmarks (direction with respect to north) with a special telescopic sighting device called an alidade. An illustration depicting the view through such a sight is shown in Figure 2.4. The bearing takers then report the measured bearings over a telephone circuit to the bearing timer-recorder.

The bearing timer-recorder (position 3 in Figure 2.1) stands at the chart table inside the pilothouse and records the reported bearings in a book called the bearing log.

The plotter (position 4 in Figure 2.1) plots the bearings that are reported by the bearing takers. He normally has no direct communication with the bearing takers, but is either told the bearings by the bearing timer-recorder, or reads them out of the bearing book as
they are written down. Once he has plotted the ship's position, the
plotter also projects where the ship will be at the time of the next few
fix observations. To do this he needs to know the heading and speed
of the ship. The plotter normally reads these from the deck log,
which is lying on the chart table beside him.

The keeper of the deck log (position 5 in Figure 2.1) maintains
the deck log in which all events of consequence for the ship are
recorded. He records all commands given by the conning officer to
the helmsman concerning the course to steer, and all orders to the
lee helmsman concerning the speed to order from the engine room.

When the projected position of the ship has been plotted, the
bearing timer-recorder consults with the plotter to decide which
landmarks will be in appropriate position for the next fix, and assigns
the chosen landmarks to the bearing takers by talking to them on the
phone circuit. In choosing landmarks, the plotter and the bearing
timer-recorder are looking for a set of three landmarks such that the
lines from the three landmarks to the projected position of the ship
intersect at reasonably steep angles. If the lines from any pair inter­
sect at a shallow angle, then a small angular error in either one will
move their point of intersection (one corner of the fix triangle)
considerably and add uncertainty to the fix. If the angles of the

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The developmental trajectory of the quartermaster

It takes about a year to learn the basics of the quartermaster's
job. For a young person learning to be a quartermaster, there are
many sources of information about the work to be done. Some go to
specialized schools before they join a ship. There they are exposed
to basic terminology and concepts but little more. In some sense,
they are "trained" but they have no experience. Most quartermas­
ters learn what to do and how to do it while on the job. Some of the
experience aboard ship is a bit like school with workbooks and
exercises. In order to advance to higher ranks, the novice must work
through a set of formal assignments that cover the full spectrum of
navigation practice and are used for evaluation of the student's prog­
ress. They must be reviewed and approved by a supervisor before
the student can progress to the next rank in the rating.

Novice quartermasters participate in joint activity with more
experienced colleagues in two contexts: standard steaming watch, and sea and anchor detail.

**Standard steaming watch**

When the ship is far from land, where the requirements of navigation are relatively light and the time pressures are relaxed, navigation is conducted in a configuration called "standard steaming watch." In this condition, a novice may stand watch "under instruction" with someone who is qualified to stand watch alone. Depending upon the level of experience of the novice, he may be asked to perform all of the duties of the quartermaster of the watch. While under instruction, his activities are closely monitored by the more experienced watch stander who is always on hand and can help out or take over if the novice is unable to satisfy the ship's navigation requirements. However, even with the help of a more experienced colleague, standing watch under instruction requires a significant amount of knowledge, so novices do not do this until they have several months of experience.

The task for the novice is to learn to organize his own behavior such that it produces a competent performance. Novices who are not capable of such organization by themselves can contribute to a competent performance if the missing organization of action is provided by the more experienced supervising watch stander. In the following example, a novice quartermaster, Seaman D, was standing watch under instruction of C. The tasks were to fill out routine position and compass report sheets. The position report requires the current latitude and longitude of the ship. D was unsure how to proceed, so C asked him to measure the latitude and longitude of the ship's current position on the chart and dictate the values to C, who recorded them on the position report sheet. Here, the labeled blank spaces on the form provide some of the structure of the task, but that structure is presented explicitly to D by C who assigns the subtasks.

Later, while working on the compass report, D was again unsure what to do. The task is to make sure the gyrocompass and the magnetic compass are in agreement. This is done by taking simultaneous readings from the two compasses and then applying corrections to the magnetic compass reading and seeing whether the corrected magnetic heading is the same as the observed gyrocompass heading. The magnetic compass reading is called the checking head, and the corrections to the magnetic compass include a quantity called deviation. While C filled in the form, they had the following conversation:

C: What's our checking head?
D: 090 and 074 [reading the gyrocompass and magnetic compasses at the helm station].
C: What's the table deviation for 074?
D: One East [reading from the deviation card on the binnacle].

In asking D these questions, C is not only getting him to practice the subtasks of reading headings from the compasses and finding deviation in a table, but is also guiding D through the higher-level task structure. D did not know what to do – how to organize his actions to get the task done. Some aspect of the organization of action required is present in the labeled blank spaces on the compass report form, but D was, by himself, unable to make use of that structure. C interprets that structure for D by asking the questions that are implied by the spaces. With C providing the organization, D becomes part of a competent performance. As D becomes more competent he will do both the part of this task that he did in this instance, and also the organizing part that was done in this instance by C. Next time D may use the structure of the form itself to organize his actions. When D becomes a fully competent quartermaster, he will not need the form at all for its organizing properties, will be able to say what the form requires without consulting it, and will use the form only as a convenient place to do the computation of corrections. I have discussed elsewhere (Hutchins, 1986) a model of psychological processes by which such organizing structure in the environment can be acquired by the individual. It is an important issue to which I will return in the discussion of the social origins of navigation competence.

**Sea and anchor detail**

Long before they are ready to stand watch under instruction in standard steaming watch, novice quartermasters begin to work as
fathometer operators and bearing takers in sea and anchor detail. The procedural decomposition of the task in this work configuration permits unskilled people to participate in complex activities. The jobs in sea and anchor detail, in order of complexity, are:

- monitoring the fathometer
- taking bearings
- keeping the deck log
- timing and recording bearings
- plotting fixes and projecting the dead reckoned track

During their individual careers, novice quartermasters move through this sequence of positions, mastering each before moving on to the next. This ordering also describes the flow of information from the sensors (fathometer and sighting telescopes) to the chart where the information is integrated into a single representation (the position fix). The fact that the quartermasters themselves follow this same trajectory through the system as does sensed information, albeit on a different time scale, has an important consequence for the larger system's ability to detect, diagnose, and correct error. To see why this is so, however, we need to consider the distribution of knowledge that results from this pattern of development of quartermasters.

**System properties**

_The distribution of knowledge_  
Knowledge in cooperative tasks is frequently assumed by analysts to be partitioned among individuals in an exhaustive and mutually exclusive manner such that the sum of the individual's knowledge is equal to the total required, and there is little or no overlap. Consider the knowledge required to perform just the input portion of the basic fix cycle. This requires the knowledge of the bearing takers, the bearing timer-recorder, and the plotter. We could imagine designing an experiment along these lines by training individuals to perform each of these roles and then putting the people in interaction with each other. This assumes no history for the participants except that each is trained to do his job. This would result in a distribution of knowledge as shown in Figure 2.5. Here the knowledge required to do each of the jobs is represented by a nonoverlapping region in the pie shown in Figure 2.5.

It is certainly possible to organize a functional system along these lines, but, outside of experimental settings, this pattern of knowledge distribution is very rare. More commonly, there is substantial sharing of knowledge between individuals with the task knowledge of more expert performers completely subsuming the knowledge of those who are less experienced. At the other end of the knowledge distribution spectrum, one can imagine a system in which everyone knows everything about the task. This too is a rare pattern because it is expensive. Splitting the task into coordinated fragments permits relatively less skilled people to contribute to task performance.

In many human systems, as people become more skilled they move on to other roles in the task performance group, making way for less skilled people behind them and replacing the more expert people before them who advance or leave the system. This is what we observe in the case of the development of navigation skills among quartermasters. A competent bearing taker knows how to do his job, but because of his interaction with the bearing timer-recorder, he also knows something about what the timer-recorder needs to do (see Figure 2.6a). The bearing timer-recorder knows how to do his
job, but he also knows all about being a bearing taker, because he used to be one. Furthermore, he knows a good deal about the activities of the plotter because he shares the chart table with the plotter and may have done plotting under instruction in standard steaming watch. What the bearing timer-recorder knows is shown in Figure 2.6b. Finally, a competent plotter knows how to plot, but he also knows everything the bearing timer-recorder and bearing takers know because he has done both of those jobs before advancing to plotting. What the plotter knows is shown in Figure 2.6c, and the distribution of knowledge that is the sum of these individual expertises is shown in Figure 2.6d. Thus, this movement through the system with increasing expertise results in a pattern of overlapping expertise, with knowledge of the entry-level tasks most redundantly represented and knowledge of expert-level tasks least redundantly represented.

**Task decompositions**

The structure of the distributed task provides many constraints on the learning environment. The way a task is partitioned across a set of task performers has consequences for both the efficiency of task performance and for the efficiency of knowledge acquisition. For example, if the decomposition into subtasks cuts lines of high-bandwidth communication (i.e., if two processes that need to share information often in order to reach completion are distributed across different task performers), the task performance may suffer from the effects of a bottleneck in interpersonal communication. The question of what parts of the process need to communicate with which other parts and how much information per unit time must be communicated is an important determinant of optimal task partitioning. This problem is evident when inexperienced bearing takers attempt to find landmarks in the world. If the bearing taker already knows how to find the landmark in question, then little information needs to be passed. The name of the landmark may be all that is required. If the bearing taker is unsure of the location or appearance of the landmark, more information may be required. For example, in the following exchange, the starboard bearing taker needs additional information to resolve an ambiguity. Here, SW is the starboard-wing bearing taker and S is a qualified watch stander working as bearing timer-recorder.

SW: (Is it) The one on the left or the one on the right?
S: The one on the left, OK?
SW: Yah, I got it.

When the confusion or lack of knowledge is more profound, it is simply impossible to communicate enough information over the phone circuit, and someone has to go in person to the wing to show the bearing taker where to find the landmark. A little later in the same exit from port, the starboard bearing taker was unable to find the north end of the Tenth Avenue terminal. The plotter C, who is also
the most qualified and highest-ranking member of the team, went onto the wing to point it out to him. On the wing, C put his arm over SW’s shoulders and aimed his body in the right direction.

C: The north one, all the way up.
SW: OK.
C: If you can’t see the light, just shoot the tangent right on the tip of the, the last end of the pier there.
SW: OK, that pier, where those two . . .
C: Yah, all the way at the end.
SW: Alright.
C: There should be a light out there but if you can’t see the light out there at the end of the pier (when we get in position), just shoot the end of the pier.

The horizon of observation

Lines of communication and limits on observation of the activities of others have consequences for the knowledge acquisition process. This is so because they define the portion of the task environment available as a learning context to each task performer. Let us refer to the outer boundary of the portion of the task that can be seen or heard by each team member as that person’s horizon of observation.

Open interactions. On a previous at-sea period, L, the deck log keeper had served as bearing timer-recorder, but his performance there was less than satisfactory. That is the job that was next in line for him, though, and he was anxious to acquire the skills required to perform the job. One of the most important aspects of the bearing timer-recorder’s job is knowing when particular landmarks will be visible to the bearing takers on the wings. One complication of this judgment is the fact that a large convex mirror is mounted outside the pilothouse windows just in front of the bearing taker on the port wing. The mirror is there so that the commanding officer, who sits inside the pilothouse, can see all of the flight deck. Unfortunately, the mirror obstructs the port bearing taker’s view forward and the bearing timer-recorder must be able to judge from his position at the

The plotter, C, the bearing timer-recorder, S, and L, were all standing at the chart table. The ship had just entered the mouth of the harbor and the team was running the fix cycle on 2-minute intervals. The previous fix taken at 36 minutes after the hour, called “time thirty-six,” was complete and C had just finished plotting the dead reckoned track out through times 38 and 40. S indirectly solicited C’s assistance in deciding which landmarks should be shot for the next round of bearings. L stood by watching what S and C were doing. All of the pointing they did in this interchange was to the chart itself.

2. C: Here’s (time) 38 [pointing to the DR position on the chart].
3. S: So it would be that [pointing to light Zulu], that [pointing to Bravo Pier]... 
4. C: One, two, three. Same three. Ballast Point, Bravo. And the next one...
5. S: (Time) 40 should be, Ballast Point...
7. S: And Balla...
8. L: He may not be able to see Front Range.
10. C: Yah, he can. Once we get up here [pointing to the ship’s projected position for the next fix].
11. S: Yah. Up there OK.
12. C: Down here [pointing to ship’s current position] he can’t. It’s back of the mirror, but as you come in it gets enough so that you can see it.

Because what S and C are doing is within L’s horizon of observation, L has a chance to see how the landmarks are chosen. Furthermore, the fact that the decision about which landmarks to shoot is made in an interaction opens the process to him in a way that would not be the case if a single person was making the decision alone. In utterance 8, L raises the possibility that the port-wing bearing taker may not be able to see the landmark. Three days earlier, on another sea and anchor detail, L had made the same suggestion about the
mirror blocking the port-wing bearing taker's view and C had agreed with him. In the present circumstances, however, L's caveat is inappropriate. S and C have already anticipated the problem raised by L, and they jointly counter L's objection, each building on what the other has said. Clearly, if L did not share the work space with S and C or if there was a strict division of labor such that people did not monitor and participate in the actions of their fellows, this opportunity for L to have even peripheral involvement in that task that will someday be his would be lost. Furthermore, L's horizon of observation is extended because the decision making about landmarks is conducted as an interaction between S and C.

Open tools. But being in the presence of others who are working is not always enough by itself. In the preceding example, we saw that the fact that the work was done in an interaction between members opened it to other members of the team. In a similar way, the design of tools can affect their suitability for joint use or for demonstration and may thereby constrain possibilities for knowledge acquisition. The interaction of a task performer with a tool may or may not be open to others depending upon the nature of the tool itself. The design of a tool may change the horizon of observation for those in the vicinity of the tool. Because the navigation chart is an explicit graphical depiction of position and motion it is easy to “see” certain aspects of solutions. The chart representation presents the relevant information in a form such that much of the work can be done by perceptual inferences. Because the work a chart does is performed on its surface - all at the device interface as it were - watching someone work with a chart is much more revealing of what is done to perform the task than watching someone work with a calculator or a computer.

The openness of a tool can also affect its use as an instrument in instruction. When the bearing timer-recorder chooses a set of landmarks that results in lines of position with shallow intersections, it is easy to show him, on the chart, the consequences of his actions and the nature of the remedy required. Figure 2.7 shows a fix that resulted from landmark assignments made by the bearing timer-recorder. Bearings off to the side of the ship rather than ahead or astern are called “beam” bearings. When the plotter plotted this fix and saw how it came out, he scolded the bearing timer-recorder.

C: What did you take a bunch of beam bearings for? Why ain't you shooting up there [points out the front window of the bridge] some place? Look what you did [points to the chart]! You shot three beam bearings. You shot three beam bearings. You better tell 'em to shoot from up ahead some place.

Once the fix was plotted, of course, it was easy for the bearing timer-recorder to see the nature of his error. Imagine how much more difficult it would be to explain the inadequacy of the landmark assignment if the lines of position were represented as equations to be punched into a calculator rather than as lines drawn on the chart.
Errors and performance feedback

The structure of the task and the extent to which the behavior of the participants is available to each other also have consequences for error detection. In the following example, the team had shot Front Range, Silvergate, and Light 2 on the previous round. S begins to make a shift that will drop Front Range on the port side and pick up North Island tower on the starboard side. He instructs PW to drop Front Range, but then discovers that SW can’t yet see North Island tower. Only a request for clarification from another sailor making a redundant plot in combat information center (CIC) makes it clear that S has decided not to shift landmarks at all and that PW has misunderstood the situation.

S: [to PW] OK, shift to Silvergate John.
PW: Drop Front Range.
S: Drop Front Range. [to SW] Steve, pick up ... ah, just stick with number 2.
PW: Alright.
CIC: [to S] Okay, John, you’re gonna shoot Light 2, Silvergate, and the Front Range, right?
S: Yah, Light 2, Silvergate, and Front Range.
CIC: OK.
PW: I thought we dropped Front Range.
S: No, picked that up because he couldn’t see the tower on this side [starboard].
PW: The Front Range and Silvergate, right?
S: Yah.

The point of this example is that the density of error correction possible depends on the horizons of observation of the team members. Here PW is on the phone circuit with CIC and S. In this case, this problem would surely not have been detected had the communication between S and CIC not been available to PW.

Supervisors are not the only ones to correct one’s behavior; a competition among peers doing similar tasks may develop. Feedback can be provided in attempts to show competence as in the following example in which PW faults SW’s reporting sequence.

S: Standby to mark time 14.
F: Fifteen fathoms.

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SW: Dive Tower 034.
PW: He didn’t say mark.
S: Mark it ... I’ve got the Dive Tower Steve, go ahead.
PW: Point Loma 339.

Here, SW was supposed to wait for the “mark” signal, but blurted out the bearing of Dive Tower when he heard the “standby to mark” signal. PW jumped on him. S then gave the “mark” signal and waited for reports, but the earlier confusion seemed to have disrupted the co-ordination of the reports and no one said anything for 2 seconds. When getting bearings, “the show must go on.” Stopping to fix the situation would ruin the fix because the near simultaneity of the observations would be violated. S minimizes the damage by acknowledging the early report on Dive Tower and asking PW to report.

If errors in the upward propagation of sensed data are not caught in the lower levels, they are likely to be noticed at the chart table by the plotter. The value of the third line in the fix is that if an error is present, it is likely to show up as an enlarged fix triangle, which will be detected by the plotter. It is, of course, possible for independent errors to conspire to produce a nice tight fix triangle that is actually in the wrong place, but such an event is quite unlikely. Now, the importance of the distribution of knowledge produced by the overlapping careers of a set of quartermasters following a career trajectory that coincides with the flow of sensed information can be stated. When an error is detected, it is detected by someone who has, at some time in his career, performed all of the transformations to which the information at hand has been subjected. This gives each task performer a much better basis for diagnosing the possible causes of any observed errors than would be the case in a system with discrete knowledge representation. When a bad bearing is reported, the plotter can examine it and may develop hypotheses about, for example, whether the bearing taker misread the gyrocompass scale, or the bearing timer-recorder mistranscribed it into the bearing book. These hypotheses are based on his experience in each of these roles.

Finally, the trainee is not the only person to benefit from error correction. Depending on the structure of the task, when feedback is given, it can be observed by others involved in the task, and their knowledge of the task system as a whole can be improved. In the previous example, for example, the fathometer operator, who has not
yet worked as a bearing taker, can learn a good deal about the task by sharing the phone circuit with the bearing takers and witnessing their mistakes and the corrections to them. In a system populated by novices and experts, many errors are likely to occur, but because there are many sources of error correction, most errors are likely to be detected. This observation leads to the somewhat paradoxical conclusion that some nonzero amount of error may actually be functional on the whole. A low level of error that is almost certain to be detected will not in ordinary circumstances harm performance; however, every error correction event is a learning context not just for the person who commits the error but for all who witness it.

Flexibility and robustness

These examples also illustrate the robustness of the system of distributed knowledge. If one human component fails for lack of knowledge, the whole system does not grind to a halt. If the task becomes difficult or communications break down, the navigation team does not have the option of stopping work. The task is event-driven and must be performed as long as the ship is underway. In response to breakdowns, the system adapts by changing the nominal division of labor. It is the bearing taker’s job to find the landmarks, for example, but if he is unable to do so, some other member of the team will contribute whatever is required to ensure that the landmarks are found and their bearings observed. This robust property is made possible by the redundant distribution of knowledge among the members of the team, the access of members to each other’s activities and the fact that the individual workloads are light enough to permit mutual monitoring and occasional assistance. Both the knowledge required to do the task and the responsibility to keep the system working are distributed across the members of the navigation team. We can think of the team as a sort of flexible organic tissue that keeps the information moving across the tools of the task. When one part of this tissue is unable to move the required information, another part is recruited to do it.

Learning to navigate

The social formation of navigation competence

In considering a novice under instruction in standard steaming watch, we observed that the structure required for the novice to organize his behavior in a competent performance was sometimes provided by the supervising watch stander. Similarly, when the quartermasters work as a team in sea and anchor detail, they each provide the others, and the others provide each, with constraints on the organization of their activities. A good deal of the structure that a novice will have to acquire in order to stand watch alone in standard steaming watch is present in the organization of the relations among the members of the team in sea and anchor detail. The computational dependencies among the steps of the procedure for the individual watch stander are present as interpersonal dependencies among the members of the team. So to the extent that the novice participant comes to understand the work of the team and the ways various members of the team depend on each other, perhaps especially the ways he depends on others and others depend on him, he is learning about the computation itself and the ways its different parts depend on each other. Long before he knows how to choose appropriate landmarks to shoot, the bearing taker learns that landmarks must be carefully chosen and assigned prior to making observations.

This point is closely related to Vygotsky’s notion of the social origins of higher mental functions. Vygotsky (1960/1981) says:

Any higher mental function necessarily goes through an external stage in its development because it is initially a social function. This is the center of the whole problem of internal and external behavior, ... When we speak of a process, “external” means “social.” Any higher mental function was external because it was social at some point before becoming an internal, truly mental function. It was first a social relation between two people. (p. 162)

Vygotsky was of course aware that internalized processes were not simple copies of external processes: “It goes without saying that internalization transforms the process itself and changes its structure and functions” (p. 163). For the sake of clear explication no doubt, and perhaps because the primary concern has been with the development of young children, many of the examples provided in the activity theory literature present cases in which the structure of the
external activity is evident and where the required transformations are fairly simple. What happens if we consider adults learning more complicated thinking strategies in more complex social settings where the primary goal is successful task performance rather than education?

If social processes are to be internalized, then the kinds of transformations that internalization must make will be in part determined by the differences between the information-processing properties of individual minds and those of systems of socially distributed cognition.

Let us consider just two such differences that were raised in the discussion of the navigation activity in its individual and socially distributed forms. First, socially distributed cognition can have a degree of parallelism of activity that is not possible in individuals. Although current research tells us that much of individual cognition is carried out by the parallel activity of many parts of the brain, still, at the scale of more molar activities, individuals have difficulty simultaneously performing more than one complex task or maintaining more than one rich hypothesis. These are things that are easily done in socially distributed cognitive systems. Ultimately, no matter how much parallelism there may be within a mind, there is the potential for more in a system composed of many minds.

Second, lacking mental telepathy, communication among people in a socially distributed system is always conducted in terms of a set of mediating artifacts (linguistic or other) and this places severe limits on the bandwidth of communication among parts of the socially distributed system. Systems composed of interacting people have a pattern of connectivity that is characterized by dense interconnection within minds and sparser interconnection between them. Cognitive processes that are distributed across a network of people have to deal with the limitations on the communication between people.

Because society has a different architecture and different communication properties than the individual mind, it is possible that there are interspsychological functions that cannot ever be internalized by any individual. The distribution of knowledge described here is a property of the navigation team, and there are processes enabled by that distribution that can never be internalized by a single individual. The interspsychological level has properties of its own, some of which may not be the properties of any of the individuals who make it up. This, of course, is no challenge to Vygotsky’s position. He did not say that every interspsychological process would be internalized, only that all the higher mental functions that did appear would get there by being internalizations of social processes.

That leads one to wonder whether there might be intrapsychological processes that could not be transformations of processes that occurred in social interaction. Finding such a process would be a challenge to Vygotsky’s position, but unless there are constraints on the possible transformations, then there is no way to identify such a process.

Clearly there are higher mental processes that could never have been realized in their current form as interspsychological processes simply because they exploit the rich communication possible within a mind in a way that is not possible between minds. Here is an example we have already encountered. The task of reconciling a map to a surrounding territory has as subparts the parsing of two rich visual scenes (the chart and the world) and then establishing a set of correspondences between them on the basis of a complicated set of conventions for the depiction of geographic and cultural features on maps. As performed by an individual, it requires very high bandwidth communication among the representations of the two visual scenes. This task appears very occasionally as a socially distributed task when a bearing taker has no idea how to find a particular landmark. In that case, the restricted bandwidth communication between the bearing taker, who can see the world, and the bearing timer-recorder, who can see the chart, makes the task virtually impossible. The spatial relations implied by the locations of symbols on the chart are simply too rich to be communicated verbally in such a way that the bearing taker can discover the correspondences between those relations and the relations among the objects he can see in the world.

Of course, it may be that the real difficulty here is simply with the volume of information to be processed and that the actual technique for reconciling map and territory was an internalization of a social activity in an environment that was informationally sparser. Without a much more detailed account of the acquisition of this process, it will be impossible to decide this case. For now, all that is possible is to raise the question of whether internal processes might exist that
are not internalizations of external processes. And doing that seems to throw the spotlight squarely on the nature of the transformation that occurs in the internalization process.

A problem of attribution

I used to subscribe to the view that all of cognitive science is basically an attribution problem. Our topic of study is, after all, a set of phenomena that are not directly observable, but only inferred from other behavior. I have now changed my mind about that. Systems of socially distributed cognition such as the navigation team seem to me to be excellent units of cognitive analysis in their own right, and understanding their operation is largely a matter of observation rather than inference.

Still, the nature of my change in mind does not change the fact that in America, at least, cognitive science in general and the current coalition between cognitive psychology and artificial intelligence in particular have adopted a theoretical stance that leads to serious overattribution of knowledge to individual actors. The basic tenet of this line of thought is that an adequate theory of cognition is one that is sufficient to account for the computational behavior observed. That in itself is not bad, but when the context of cognition is ignored, it is impossible to see the contribution of structure in the environment, in artifacts, and in other people to the organization of mental processes.

If the individual mind itself is the only locus considered for the structures that organize thinking, then everything that is required to create a sufficient account of cognitive activity has to be crammed into the individual mind. This leads the followers of this view to try to put more in the individual mind than belongs there. The properties of groups of minds in interaction with each other, or the properties of the interaction between individual minds and artifacts in the world, are frequently at the heart of intelligent human performance. But attributing them to individual minds hides them from analytic view and distorts our understanding of the processes that do belong to individual minds. As long as the nature of the shaping of thought by context is not seen, the organization of mental function that must be attributed to individual minds to account for observed performances will not be of the right sort.

Notes

1. On other ships, and on this ship in different circumstances, the team may be somewhat larger or smaller depending on the availability of qualified personnel.
2. In fact, the two quartermaster chiefs with whom I worked most closely said they preferred to get their trainees as able-bodied seamen without any prior training in the rate. They said this saved them the trouble of having to break the trainees of bad habits acquired in school.
3. This example and all of those that follow come from a corpus of video and audio recordings collected by the author during fieldwork aboard U.S. Navy ships. All of the events described are the activities of a real navigation in real operations.

References