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Spatial Conception of Activities: A Socio-Cognitive Perspective for Simulating Work Practices

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Abstract

People conceive their everyday affairs (their practices) as social actors in activities, in which they perceive, infer, move, manipulate objects, and communicate in some physical setting (e.g., going to the grocery to buy dinner). These behaviors are conceptually choreographed in an ongoing, usually tacit understanding of "what I'm doing now," encapsulating *roles* ("who I'm being now"), *norms* ("what I should be doing"; "how I should be dressed/talking/sitting"), and *progress appraisals* ("how well I'm doing"). Activity motives and modalities vary widely (e.g., waiting in line, listening to music, sleeping), all of which require time and occur in particular settings.

Brahms is a multiagent work systems design tool for modeling and simulating activities, used extensively to design aerospace work systems. For example, the Generalized Überlingen Model (Brahms-GÜM) simulates air transportation practices, focusing on how pilots and air traffic controllers interact with automated systems in safety-critical, time-pressured encounters. Spatial cognition is pervasive: Scanning displays of multiple workstations; coordinating airspaces and flight paths; prioritizing and timing interventions to maintain aircraft separations.

Brahms-GÜM demonstrates how events may become unpredictable when aspects of the work system are missing or malfunctioning, making a routinely complicated system into one that is *cognitively complex* and becomes out of control. Normally asynchronous processes become coupled in space and time, leading to difficulty comprehending the situation ("what is happening now") as a familiar multi-modal flow of events. Such examples illustrate the dynamics of spatial cognition inherent in our *conceptually situated* experience—our consciousness—of who we are and what we are doing.

Keywords: Work practice; cognitive process model; behavioral simulation; situated cognition; complex systems.

Problem and Objective

The Brahms Generalized Überlingen Model (Brahms-GÜM; Clancey et al. 2013) was developed as part of ongoing aviation safety research to extend human-system performance modeling from the individual level (one user, one task, one display) to the level of multi-agent teams (a choreography of people and automated systems). In particular, the research theme of "authority and autonomy" focuses on how roles and responsibilities are distributed and reassigned among people and automated systems to handle routine tasks (e.g., autopilot modes) or resolve dangerous situations (e.g., collision avoidance alerts).

Brahms is a multi-agent simulation system in which people, tools, facilities/vehicles, and geography are modeled explicitly (Clancey et al. 1998; 2005). In Brahms-GÜM the air transportation system is modeled as a collection of distributed, interactive subsystems (e.g., airports, air-traffic control towers and personnel, aircraft, automated flight systems and air-traffic tools, instruments, crew). Each subsystem, whether a person, such as an air traffic controller, or a tool, such as the Air Traffic Control Center (ATCC) radar, is modeled independently with properties/states, beliefs/mental models, and contextual behaviors. The simulation then plays out the interactions among these separately existing models of subsystems.

The 2002 Überlingen mid-air collision was chosen for this experiment using Brahms because systems like the Traffic Alert and Collision Avoidance System (TCAS) deliberately shift authority from the air-traffic controller to an automated system. The Überlingen accident provides a starting point for exploring authority–autonomy conflict in the larger system of organization, tools, and habitual behaviors (practices) that contextually affects attention, deliberation, and action (Clancey 1997, 2004). In particular, a person/system can have more than one role at a given time, and responsibilities can be reassigned during operations in a situation-dependent manner. For example, we can simulate that when an air traffic controller (ATCO) goes on a break, as occurred at Überlingen, another ATCO shifts to handling multiple workstations. Simulated pilots and ATCOs also have multiple behaviors dependent on the socio-cognitive context for communicating, following directions, and interacting with automated systems.

Modeling and Simulation Method

A work practice simulation represents chronological, located behaviors of people and automated systems. In contrast with task models, which represent abstractly what behaviors accomplish (i.e., functions), a *behavioral model* represents what people and systems do, called *activities* (Clancey 2002). Activities include monitoring (looking, attending), moving, communicating, reading and writing, all of which require time and occur in particular places with other people, tools, materials, documents, and so on. In terms of work, a function/task model characterizes what a person or system does (e.g., "determine the altitude"), and a cognitive-behavioral model of practice represents how the work is carried out in the world (e.g., simulate a person moving, changing the state of a control, perceiving a display's representation, and inferring a problem exists).

A fundamental function of higher-order consciousness is that behavior is *conceptually situated* (Clancey 1999, 2008). People conceive their everyday affairs (their practices) as social actors in activities, in which they perceive, infer, move, manipulate objects, and communicate in some physical setting (e.g., going to the grocery to buy dinner). These behaviors are conceptually choreographed in an ongoing, usually tacit understanding of "what I'm doing now," encapsulating *roles* ("who I'm being now"), *norms* ("what I should be doing"; "how I should be dressed/talking/sitting"), and *progress appraisals* ("how well I'm doing"). Activity motives and modalities vary widely (e.g., waiting in line, listening to music, sleeping), all of which require time and occur in habitual settings.

Brahms was specifically designed as a work systems design tool for modeling and simulating activities. The Brahms-GÜM simulation is based on a fine-grained analysis of the published events of the Überlingen collision, relating spatial and temporal interactions of: 1) information represented on displays and documents at the air traffic control center and in the cockpit, 2) what controller(s) and cockpit crew were individually doing and observing, 3) alerts provided by automated systems, 4) communications within the cockpit and with air traffic control, 5) control actions to change automation and aircraft flight systems, 6) people's beliefs and reasoning regarding responsibilities of individuals and automated systems, progress appraisal of assigned responsibilities, and resolution of conflicting information/directives.

The Überlingen case is of special interest because TCAS gave advice to one flight crew just seconds after they had already begun to follow a different directive from the Zurich air traffic controller. Psychological, social, and physical coordination issues are potentially involved in disengaging from an action in process that may make it difficult or impossible to follow the required protocol of following TCAS and ignoring the ATCO.

The Brahms simulation model constructed in this research is not merely a replication of the Überlingen collision, that is, a hand-crafted, single scenario of events. Rather Brahms-GÜM consists of a *generalization* of all the subsystems (e.g., phones, radar, alert systems, aircraft, pilots, air-traffic controllers, ATCCs) that played a role in the Überlingen collision. Rather than only representing the states and behaviors of subsystems at the time of the collision, Brahms-GÜM represents their normal states and behaviors, and allows for them to be configured for each simulation run to characterize alternative behaviors, including absent, alternative, and dysfunctional or off-nominal forms (e.g., a pilot can follow TCAS or ignore it; the phones in an ATCC are not operating; a scheduled flight departs late).

Each of the many possible configurations of Brahms-GÜM parameters defines a scenario. Because of the variations in initial facts, beliefs, and properties/states and the probabilistic activity durations, each simulation run produces time-space-state interactions with potentially different outcomes. For example, in some configurations of Brahms-GÜM, the Zurich ATCO notices the imminent collision and advises pilots before TCAS issues a traffic advisory. The combinations of all possible parameter settings define a space of scenarios that Brahms-GÜM should be able to validly simulate. What occurred at Überlingen is one scenario in that space.

Simulating Spatial Cognition

Spatial cognition is pervasive in air transportation systems. In particular, challenges and errors occurred at Überlingen because of spatial relations in the work system and how they were perceived and comprehended by the air traffic controller and pilots. Most notably, the ATCO is managing multiple flights with potentially intersecting paths in an airspace sector. These flights are represented both on written "control strips" that designate a sequence of waypoints and on radar displays. During the Überlingen situation, a single ATCO was managing both the sector and the local airspace relevant to the Friedrichshafen airport, represented on the radar displays associated with two workstations that he had to move between. The workstations were tuned to different radio frequencies, and ATCO needed to move to hear and speak with pilots. Brahms-GÜM simulates what is displayed on each screen every second (as propositions), what can be heard (location dependent), where the ATCO is located, what part of the radar display ATCO is scanning, the flight data read, and what is heard on the workstation's associated radio.

The most obvious form of spatial cognition is the requirement to coordinate flight paths and transfer each flight to another ATCO as it nears the boundary of the sector. ATCO is responsible for keeping planes separated vertically and within a given altitude. The Short Term Collision Avoidance (STCA) system warns ATCO when aircraft trajectories risk violating the required separation. Because it was disabled during maintenance, STCA was not functioning when the Überlingen collision occurred.

TCAS is the corresponding spatial alert system for pilots. Pilots have different roles for monitoring activities during flight and will differentially perceive and gain information from displays that not everyone can see. In the aircraft that failed to follow TCAS instructions, although everyone could hear the "Traffic! Traffic!" alert, a junior pilot seated by the TCAS display reported "It says climb" to the Commander, who chose to follow the ATCO's contrary instruction instead. The pilots were further confused because the ATCO gave the wrong location for the intersecting flight, leading them to waste time looking for a possible third plane. Pilots are also familiar with false alerts caused by converging flights approaching different runways of a busy airport, which an ATCO may call out for pilots to visually confirm.

During the 25 minutes before the Überlingen collision, temporal-spatial relations required the ATCO to repeatedly shift between workstations, as he interacted with different flights, displays, telephones, and radios. At a key moment, when the west-bound Russian flight announced its arrival in his sector, he failed to handle its altitude being the same as the north-bound DHL flight he approved some moments earlier. He was apparently preoccupied by difficulties contacting the Friedrichshafen tower for a late-arriving flight that had just interrupted him by calling in on the workstation assigned to the local region. Thus he was juggling not only flights but his physical location and his conceptualization of multiple activities with different interactive protocols and priorities involving multiple tools (phones, radio, radar, STCA). The spatial-temporal proximity of events was unfamiliar, and processes became causally dependent on each other. ATCO's ongoing conscious effort to conceptually coordinate "the situation" and what he *should be* doing broke down.

Results and Conclusions

Experimentation with Brahms-GÜM reveals that timing of events at the level of a few seconds makes a substantial difference in the simulated outcomes. In particular, because TCAS's advice does not consider what the people are saying and deciding among themselves, the work system design is especially vulnerable if ATCO intervenes with pilots a few seconds before TCAS generates a resolution advisory, which is what happened at Überlingen.

We had not encountered such sensitivity to timing and emergent interaction sequences in any of the prior Brahms models created over two decades. Brahms-GÜM simulates how subtle issues of timing in human-automation interactions arise when degraded or missing subsystems result in lack of information and inability to communicate, transforming a given configuration of flights that are routine in a normal work system to a situation too complex for the overall work system to handle safely.

In particular, the events in the air traffic control center reveal how after people develop work practices in which they rely on automation (e.g., STCA), the absence of automation may cause the workload to increase and the evolving situations to become too causally co-dependent to appropriately prioritize tasks or delegate responsibility. The sequence of events may become unpredictable when aspects of the work system are missing or malfunctioning, making a routinely complicated system into one that is *cognitively complex* and thus out of human control. Normally asynchronous processes become coupled in space and time, leading to difficulty comprehending the situation ("what is happening now") as a familiar multi-modal flow of events. Hence, complexity is relative to a person's knowledge, beliefs, roles, habitual procedures, and tools. Specifically, ATCO was required to conceptually coordinate multiple recursively nested action sequences that were interrupted, perhaps related to short-term memory limitations in natural language comprehension (Clancey 1999; 2005; 2006).

Brahms-GÜM demonstrates the strength of the framework for simulating behaviors of asynchronous (or loosely coupled), distributed processes in which the sequence of interactions can become mutually constrained and unpredictable. Creating and experimenting with work practice models reveals interactions that are omitted, glossed over, or difficult to comprehensively describe in accident reports. The simulation generates metrics that can be compared to observational data and/or make predictions for redesign experiments.

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