Construction of Shared Situational Awareness in Traffic Management

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The construct of "situational awareness" (SA) has a rich and productive history within both academic literature and practice. Situational awareness as a technical term has its earliest roots in formative human factors research in service of military and flight applications. However, its value as a construct in other domains, particularly those having to do with rapid sensemaking in safety-sensitive conditions, has led to a broader applied and theoretical interest over the past few decades. As a discipline, CSCW has been relatively less engaged with this concept, but has empirical and theoretical tools that will be valuable to its study. To bring CSCW more fully into the conversation, we present a description of how operators in a city department of transportation's transportation management center (TMC) develop and maintain situational awareness for themselves and the key recipients of their critical information outputs. We identify some of the schemas operators must develop in order to effectively construct situational awareness and dynamically articulate common fields of work, and the social collaborative practices they engage in to support that awareness. Implications for design and further research are proposed.

CCS Concepts: • Human-centered computing~Collaborative and social computing~Collaborative and social computing theory, concepts and paradigms~Computer supported cooperative work • Human-centered computing~Collaborative and social computing~Collaborative and social computing design and evaluation methods~Ethnographic studies

KEYWORDS: Situational awareness; common field of work; control rooms; transportation; distributed cognition

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1 INTRODUCTION

As cities in the US grow, infrastructure like roads are becoming increasingly crowded and stressed. In these environments, it is important to have adequate traffic management, so that when something does go wrong (such as an accident, a broken down car, or even a major crime where response requires closing roads), it can be quickly and safely addressed and handled. Addressing this sort of issue requires an intensive form of coordination between different parties—such as police, fire departments, traffic managers, and the public—who are grappling with rapid, and sometimes high-stakes, changes in available information. Keeping an up-to-date understanding of what is going on and how it should best be addressed requires operators to construct and maintain what is often called "situational awareness." But what is "situational awareness"? Is it the ability to perceive and judge relevant phenomena, a posture of attunement to sensory information, an epiphenomenon of coordination between different people, or something else? This construct has been studied extensively and generated a variety of theoretical and methodological frameworks for measuring and assessing it.

In our study, we were drawn to the idea of situational awareness as an organizing concept for two primary reasons. The first reason was that it was a concept that seemed important to the people we were observing (operators at a traffic management center in a major American city). They used the term relatively frequently to point to an aspirational level of performance in their job, an indication that all of the pieces were coming together to manage traffic incidents and congestion effectively. Thus, it became important for us to understand the value of this term for orienting their own activities in a fast-paced, ambiguous workplace. Once we began comparing operators' accounts to existing literature, we realized that there was a theoretical and methodological richness to the concept that bore further exploration. An aspect of our setting that makes it particularly interesting to study from the point of view of situational awareness is that it simultaneously embodies two different views of SA: that of an attitude or position of awareness (a "situated awareness," perhaps), and that of a skilled awareness *of* a particular *situation.* That is to say, operators must both cultivate and maintain a posture of awareness, and work together to qualify any of the wide variety of phenomena they are observing as "situations"; then package their observations and actions to support the work of other entities. It should be noted that the term "situation awareness" and "situational awareness" are both used in the literature and in practice. In this paper, we will use "situational awareness" because 1. it is the term most commonly used by our participants; and 2. we find "situational" to more naturally encompass these two different senses of the term than "situation," which (to our reading) more strongly implies the existence of a singular "situation" rather than a continuous stream of reality that humans must reify according to their own understandings.

Combining our own observations with prior work, we identify several key components of situational awareness for these operators: an ongoing, culturally reinforced posture of awareness situated in the schemas of technology tool assemblages and patchworks of jurisdiction developed by experience; an adequately complete picture of specific, qualified situations partly captured via data collection practices; and specifically tailored versions of awareness of situations sent to various audiences and projections concerning what effects those messages will have on the situation itself. We can see the operators as standing in the middle of an informational pipeline: they must observe the sometimes undifferentiated flow of information coming from their working tools, and qualify it as something needing action; and

then must compose and transmit that information outside of their own work setting, thereby creating appropriate situational awareness in a variety of others. Their own situational awareness is both the output of their work processes, and input into the situational awareness of other, very different groups and individuals.

Focusing on the unique place the operators occupy in the "informational pipeline" of situational awareness adds needed nuance to the existing accounts of situational awareness, and suggests opportunities for CSCW approaches to improve both the situational awareness of operators and the quality of life of those they serve. We will elaborate the connections between trans-individual situational awareness and the influential CSCW concept of the "common field of work". The activities of the operators support the contention in the literature that SA is difficult to analyze via determining whether objectives have been accomplished, as 1) they have limited control over task orchestration and must accomplish many of their objectives via requests and communication; and 2) their work is often focused on mitigation of ongoing incidents, making success difficult even to define within an individual incident. Operators must instead remain aware of their place within a partial and ambiguous locus of control to help the city keep the roads moving. In the Findings, we will go into depth about one particular anecdote that more clearly illustrates how this works.

2 PRIOR WORK

The term "situational awareness" arose from military and flight contexts, possibly as early as World War I [1]. Beginning in the 1980s, following growing interest in the human factors community, Mica Endsley proposed what has been probably the most influential model of situational awareness (or in her phrasing, situation awareness; though again, we will be generally using "situational awareness" throughout except within quotations), the three stage model. Endsley's model was the first to be widely cited and adopted, and emphasizes *stages* that an individual human undergoes to successfully accomplish situational awareness. The first stage is perception, often visual or auditory, of objects and their states. The second is comprehension: the understanding of what is relevant among what has been perceived. The third stage is projection: extrapolating what effect the synthesized information will have upon the operational environment [2]. In Endsley's original model, situational awareness is part of a larger process, serving as input into decision-making which is then an input into action. In general Endsley attempted to shield the term from too broad an application, particularly earlier in her work on the subject: "SA as defined here does not encompass all of a person's knowledge. It refers to only that portion pertaining to the state of a dynamic environment. Established doctrine, rules, procedures, checklists, and the like-though important and relevant to the decision-making process-are fairly static knowledge sources that fall outside the boundaries of the term" [2].

Part of what makes Endsley's model so influential is how, in a sense, underspecified it is. It invites questions. Is *any* entity capable of moving through these stages "situationally aware"? If so, does that mean groups of humans can achieve a "shared" or "distributed" or "team" situational awareness? How similar does their mental state (on the cognitive side) or operational goal (on the behavioral side) have to be to count? Can non-human entities contribute to, partake in, or even independently obtain situational awareness? For the purposes of observation and measurement of SA, or operationalization of the term in research or design, what apparatus do we need in order to claim that we observed situational awareness?

Attempts to grapple with these questions have stimulated useful critiques. As early as 1995, Flach cautioned against the tendency in some research to identify SA as not just a cognitive phenomenon but an objective *cause* of anything, such as military error [3]. Similar to other terms such as "infrastructure" [4] or "organizations" [5], the aspirational connotations of the term and the many accounts of its "true" nature without much recourse to empirical justification may cause some in CSCW to be somewhat hesitant to study it seriously. Part of the project of this paper, then, is to sharpen and specify the theoretical work the term situational awareness might do for us.

2.1 Situational Awareness Beyond the Individual

As scholars have examined situational awareness with greater care in a greater variety of disciplines, questions have emerged about how SA might function in a more expansive setting than the mind of a single person. After all, most contexts where situational awareness is relevant are multi-party, coordinated work settings--similar to those where foundational CSCW workplace studies were done (such as the Heath and Luff analyses of London Underground operators) [6]. Indeed, this seminal work itself describes the importance of something that appears to be very similar to a form of situational awareness that different operators need to share: "Without knowledge of the current 'state of play', the timing and movement of vehicles at this moment at time, the development of the service and any difficulties on this particular day, the Controller and DIA would be liable to draw the wrong inferences from the various sources of data available to them. There would be a risk that the wrong decisions would be taken and misleading information would be provided to both staff and passengers. The intelligibility of the scene, the possibility of coordinating tasks and activities, rests upon these socially organised and communicative practices." In our field site, for instance, one of the operators' primary tasks is packaging and delivering messages about a situation to different sorts of audiences, and efficiently coordinating between themselves. One expansion of the concept beyond the individual perceiver is the idea of "team" situational awareness. According to Endsley's recent handbook on designing for SA, a "team" is not just an assortment of individuals. Rather, it is a group of people with a common goal, with defined roles that are at least somewhat interdependent [7]. The degree to which persons on the team have shared SA requirements is determined by the overlap between their goals. Breakdowns or inaccuracies in shared SA may require individual SA to notice and repair problems [7].

Might SA extend even beyond a "team"? To understand the dynamics of situational awareness in teams and groups more fully, researchers have turned to literature on distributed cognition, which refocuses attention on the way that awareness might be established across an interacting group of people, interfaces, and objects. Hutchins and Klausen's 1996 study on distributed cognition in airline cockpits [8], for instance, shows how pilots use the cockpit as a cognitive extension in order to manage the severe load of cognitive tasks, and how using the entire cockpit as the cognitive unit of analysis allows the system to be "greater than the sum of its parts." In an influential paper on "distributed" situational awareness, Artman and Garbis critique Endsley's "mentalist" assumptions about SA: "SA becomes another box in the individual's mental machinery, 'an individual act bounded by the physical facts of the brain and body' (Resnick, 1991:1). The strong mentalistic and individualistic bias … has lead [sic] SA studies to focus on first person experienced perceptions. These constraints in theory and practice have reduced SA to be an individual mental skill or ability (McMillan, Bushman & Judge, 1995). In the pursuit of a method to unfold this skill or ability, sense-making negotiation

and interactive processes as well as technological support are forgotten" [9]. Inaccuracies or disharmonies are, then, not necessarily errors to be corrected with individual SA, but to be worked out via shared sensemaking. Finding the theoretical basis of existing works on "team" or "shared" SA too vague, the authors claim that a distributed cognition approach is not only more theoretically satisfying, as it supports the kind of real phenomena people undertake as they create situational awareness with other interactants; but is also more amenable to valid analytical measurement because it emphasizes (at least partially) interaction rather than internal mental states.

2.2 Studied Settings

Much of the work on situational awareness has focused on safety-critical work settings such as aviation [10], medicine [11,12], and cyber security [13]. However, some work, for example in road safety, does try to understand the situational awareness of drivers and even the road system itself. A review of SA for road safety [14] (encompassing both driver awareness and the supports offered by road safety systems overall) overtly takes a loose distributed cognition approach in its argumentation for the addition of a "systems" or human factors approach, which allows for entities to share in a larger situational awareness while not having *identical* awareness simultaneously. Yet while the authors do not explicitly mention actor-network theory, their language about infrastructure elements helping to establish SA does have a certain flavor of non-human actors helping not only to offload cognitive effort, but also to exert agency in maintaining safety throughout the road system: "From the systems viewpoint, rail level crossing operation (i.e. safe interaction of trains and road users) is distributed between various agents, including road users, the train and train drivers, the level crossing infrastructure and other elements of the road system such as signage and road markings. Neither drivers, other road users, train drivers nor artefacts (e.g. vehicles, in-vehicle displays, road infrastructure) alone hold adequate SA to allow safe operation of the level crossing. Each component holds a compatible portion of SA which, when connected together through SA exchanges (labelled transactions), enables the level crossing system to function effectively. For example, the driver holds SA regarding the goals of the driving task, operational aspects of the driving task (e.g. position on road) and route information (e.g. directions required to achieve driving goals)" [14]. This "system SA" concept has implications for many of the automated tools being developed to assist operators identify and address issues more quickly. An imputation of "awareness" to some entity that is not purely human, even if in part, opens up opportunities for automated tools to participate meaningfully in situational awareness. Growing such capabilities enables a region such as a city to expand situational awareness in scope and scale, but also raises new challenges for verifying and combining these new signals to allow responders and managers to act appropriately (as in, for example, multi-modal changes to emergency response in Ecuador, and the new protocols for evaluating signals when signals came from a variety of novel sources, such as social media) [15].

More distributed notions of situational awareness have been taken up in recent work on social news, particularly with regard to the spread of different potential sources of information. Congosto, et al. [16] analyzed Twitter as a social "sensor" for changes in transportation situations. Earlier work by Vieweg, et al. [17] showed the potential capacity for Twitter to help produce situational awareness, and even suggested that this informational relationship was an even broader conception of distributed cognition, as it would include a sending and receiving public. In our case, TMC operators do not take full advantage of Twitter's "sensing". They do,

however, tailor public messages and produce them in accordance with existing information structures, creating a type of carefully crafted "situational awareness" within their reading public. How they should process and verify information coming in from the public, however, is sometimes beyond the remit of their responsibilities. It is, however, an interesting and potentially valuable avenue for further improvement of their work.

All of this ambiguity, where operators are partly responsible for determining whether some particular slice of traffic behavior can be called an "incident" and which sources of information are relevant in producing that judgment, requires coming to a shared discrete understanding of a continuous situation, a key output of sensemaking. Several studies have examined the role of formal and informal sensemaking activities in helping to support situational awareness (e.g., [18,19]). The varied processes of sensemaking allow the operators to not only offload cognitive load to the system, but also help to maintain their higher-level understanding of broader traffic trends and thus act more effectively in the future.

Organizational studies has also had a keen interest in concepts related to situational awareness. Since most descriptions of situational awareness focus on high-pressure environments where people and organizations must quickly make sense of challenging situations, SA is in a sense a distillation of some of the concerns of organizational studies in general. In particular, Weick and Sutcliffe's [20] identification of "sensitivity to operational conditions" is a more effortful and extensive version of situational awareness in high-reliability organizations. High-reliability organizations are those that manage to avoid failure despite working in environments of high risk. To maintain that reliability, they must be vigilant and skilled, and have highly effective and resilient processes, and that means developing a discipline of situational awareness, for at least some of their organizational units. The emphasis is on a broad and strenuous awareness of current conditions, primed to the possibility of failure that could arise at any time.

2.3 CSCW

Much research in CSCW has examined concepts of "awareness," but little has gone into great depth about the idea of "situational awareness" specifically. For example, Gutwin, et al.'s classic works on workspace awareness helped identify the characteristics of fluid shared awareness of work processes and objects that allow collaborative in-person work to happen, and established a rich and productive line of work [21]. Though much like situational awareness, this term is not without its critics. Schmidt argues that studying awareness *per se* is a dangerous venture because it is not a coherent construct or imputes too much identifiable structure to a too-wide variety of phenomena [22]. Wong and Neustaedter [23] do examine SA specifically. They analyze the tools used by flight attendants and how they support or obstruct their situation awareness in the air. The concept of SA is operationalized fairly simply because the focus is on the tool needs of the flight attendants. In Conversy, et al. [24], situational awareness is described as something that can arise naturally from the right configurations of tools. This idea of "awareness" is a more specific and granular lens on sensory perception of what collaborators are doing than on understanding a phenomenon via shared tools. For example, Hornecker et al. [25] contains experiments to determine via behavioral indicators whether mice or touchscreens supported more awareness between collocated collaborators. Attempts to measure this sort of awareness directly have been difficult, since it is an individual internal state that may or may not give rise to observable behaviors or successful task accomplishment. This mirrors many of the difficulties in measuring and assessing situational

awareness. For this reason, much empirical work has focused on indicators such as gaze and proximity [26, 27]. For our purposes, the shared awareness of others' actions in a common technology environment and toward a common objective is a key part, but not the entirety, of situational awareness. Even in Hong, et al. [28], which does directly seek to improve situational awareness via an automated visualization tool, relies on a certain level of abstraction from the "situation" itself. Another study [29] of coordination during military simulations also aims to create automated supports.

Using the particular methods and frameworks of CSCW to refine our understanding of what SA is, where it can be improved, and what its limits are, have typically fallen outside of CSCW's disciplinary interest, especially with the gradual turn away from strictly workplace studies. Yet as we have seen, there is significant interest in CSCW's classic (high-intensity workplaces) and current (social media coordination, the principles and limits of automation) interests. Yet some additional conceptual bridging may be useful. To that end we would like to briefly examine how two concepts core to CSCW both classic and recent, articulation work and the common field of work, offer insights into 1. How situational awareness is produced between multiple parties and 2. How coordination works in these sorts of fast-paced, dynamic environments.

A concept that may help to unite trans-individual situational awareness and CSCW is that of the "common field of work." This concept introduced by Schmidt [30] was used to explain how people coordinated: by changing the states of their common field of work. This is a "conceptual construct" to help us understand cooperative work. As they describe it, "The field of work and the cooperative work arrangement mutually constitute and delimit each other. The field of work is always the field of work for a particular cooperative work arrangement and the cooperative work arrangement is itself bounded and constituted by the interdependence of its activities as determined by the field of work." They also describe the field of work as a manifold and recursive, encompassing both tools and processes; and the field of work in one setting can serve as a component of the field of work for another. Finally, its boundary and character are dynamic, changing in scope and participants: "For example, when a ship meets another ship during its voyage, the field of work of the crew — basically, the ship and the water — "suddenly expands to include another ship" (Perrow, 1984, p. 178). " In multi-agency response to problems, this sort of expansion must happen all the time. Other parties join and reconfigure the common field of work, and by doing so attain appropriately shared situational awareness. Additionally, to look at trans-individual situational awareness as the articulation [31] and rearticulation of overlapping common fields of work helps to center coordinative practice, which is a key strength of CSCW. It also offers a lens on SA that has less frequently been attained: a more contextual, ethnographic understanding of how operators learn to create and share the structures that enable effective SA in the moment.

3 METHODS AND SITE DESCRIPTION

The site covered in this research is a local, government-run traffic management center (TMC) in a large American city. This TMC is a division of the city DOT (department of transportation), and is responsible for monitoring emerging and ongoing traffic issues on major city arterial roads and on some highways, and helping to coordinate response to such issues. The TMC is primarily concerned with incidents that might block traffic. Though we immediately think of car wrecks as the main culprit, there are many situations that require a response -- such as debris on the road, suicide attempts, traffic light errors, sporting events, and others.

Four of the authors conducted observations at the TMC and in-depth interviews with operators and some related personnel over April and May 2019, and the first author had a pre-existing action research relationship with some of the participants. On average, four of the authors spent about four hours each per week observing during the course of the study. The authors varied their observation times to ensure that they were able to see a variety of activity types (such as rush hour or late night slumps) and interact with different operators on duty.

During each observation, the authors took field notes which they transcribed as data and shared with the team weekly. Using a modified grounded theory approach, the authors reviewed each other's field notes regularly, looking for themes and writing corresponding memos. A large number of themes emerged from this initial memoing phase, including a strong focus on situational awareness as a term used by the operators themselves. Given the centrality of situational awareness to the work that goes on in the TOC, the authors were eager to pursue the "indigenous meaning" of this term, and develop an understanding what operators themselves made of the term and what role it played in their work. Through weekly group discussions, the authors decided to turn their attention to this term and related themes throughout the rest of the observation, and later memos and codes therefore centered more closely around this concept.

Observations and field notes surfaced a number of salient aspects of work in the TOC that the group used to develop an interview protocol. Interviews were conducted toward the end of the observation period and after it was complete. Overall, the interviews included 11 individuals from the TOC and DOT, including seven operators (all of whom the team had interacted with during observations), the manager of the TMC, and three DOT employees whose work intersected with that of the operators. One of these three DOT employees had previously worked as an operator in the TMC before being promoted to a data analytics position. These interviews added valuable context to the existing themes and inspired new connections to what we had been observed.

Coding began early in the research process, with each author individually coding field notes and then interviews. This followed an open coding approach [32], meant to generate a large number of codes and themes without avoiding overlap, or restricting thematic generation to the notion of situational awareness. Through group meetings, the authors compared codes, merging some and separating out others. As the research team became increasingly sensitized to the concept of situational awareness, the low level descriptive codes and higher level themes were tightened around that concept as it appeared in the data. Once most of the data had been captured, the authors collaboratively developed a codebook which included seven overall themes from the data and thirty-seven sub-themes. These were used by the team to revisit all data (observations, memos, and transcribed interviews) through a process of axial coding. Multiple authors revisited each piece to apply relevant codes. From this analysis, the team developed theories encompassing the themes and wrote an internal paper describing the findings.

Months after this first phase of data collection and coding, the first author dove into literature on situational awareness and began a kind of conversation between the text and this data. With a better understanding of existing literature and this work's contribution, the first author revisited the data and began forming the analysis encompassed in this paper.

IRB approval was obtained for our observations and interviews, and pseudonyms have been used for each of the participants. A report of our key findings was sent to the manager of the TMC following our data collection period.

Table 1: Interviewees

Pseudonym	Role
Harun, Zeke, Todd, Sarah, Jacob, Adrian, Faraj	Operator
Jim	TMC manager
Brandon	City DOT data analyst
Amadi	City DOT traffic engineer
Kate	City emergency manager

3.1 Operators' Work Settings and Activities

Operators usually occupy their position for approximately two years, and generally have civil engineering backgrounds. While a number of the participants were looking ahead to careers in either the state or city DOT, most were at the beginning of their career and did not have much direct prior experience in traffic management before becoming an operator. The operator position is, in this particular context, seen by many as a steppingstone to other, more specialized roles within the city's DOT. Some of the participants were from the local area, and were able to draw on some familiarity with the city, but, as we discuss below, there was a great deal of expertise around camera positioning and navigating agency jurisdictions that could not be drawn from a general familiarity with the city, and had to be learned on the job. The training cycle lasts about two months, which includes familiarization with SOPs (standard operating procedures) and other documents, then shadowing more experienced operators, and a gradually increasing level of autonomy in actually handling incidents.

During their work, operators, usually two at a time except during the less-busy night shift, sit in a fairly dark room with four desks (which are meant to be interchangeable and not dedicated to an individual, since the room is small and runs 24/7). Someone must be available in the TMC at all times; the office maintains a cell phone that the office phone forwards to that operators take if they are working alone and leave the room. Three of the four desks face a grid-like wall (the Camera Wall) displaying 36 live video streams of areas around the city. They typically use this wall, plus the two monitors on their desk, to do their work, much of which is searching for and manipulating the views provided by the roughly 250 cameras the city's DOT operates around key parts of the city. They use a client to manage these cameras (which we will call the Camera Management Tool, or CMT), and typically one of their workstation monitors is dedicated to this client. They can use the client to project any specific camera feed to the camera wall that they face while they work, and less frequently, to change the configuration of the camera wall. The client allows them to rotate and zoom the cameras, to save custom rotation settings, and in some cases even to use windshield wipers to keep visibility good during rainy conditions. The client also connects to city-owned dynamic message signs (DMSs)--the signs that show travelers on the road brief warnings about wrecks, construction, etc. (Example: "CRASH 1 MILE AHEAD / LEFT LANE CLOSED").

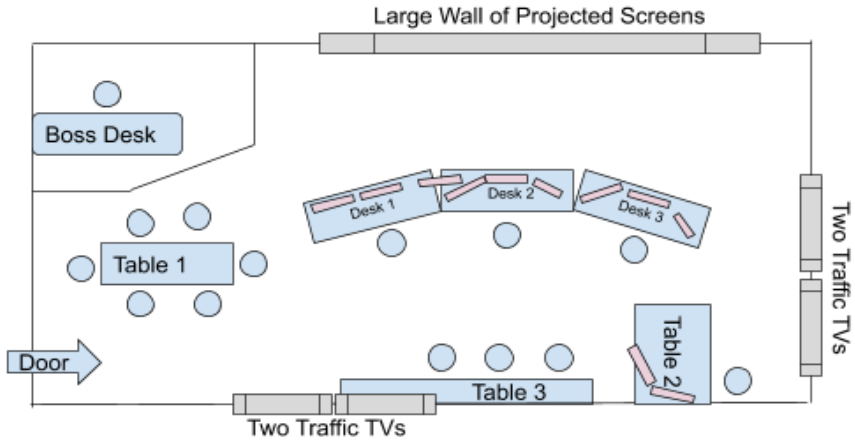

Figure 1: General layout of the TMC

While operators watch and search the camera feeds with their eyes, they can also hear a continual readout of the radio chatter from some of the first responder agencies' dispatchers. For long stretches of time, the radio chatter and the hum of computers is the only sound in the windowless room, especially when the gregarious manager Jim is in his own office working. On their second monitor, they can also see a (partial, redacted) readout of the computer aided dispatch (CAD) systems from the city police and fire departments. There is significant, but not perfect, overlap between the information in the radio chatter and the CAD readout.

The operators spend their time watching the constant stream of video feeds on the Camera Wall, most of it routine traffic that requires no action or special attention from them. While there are usually two operators working at once, their chatter is infrequent; most of them are habitually quiet and took some time to become comfortable with our presence, although they were consistently pleasant and generous with explanations. Their growing comfort was often indicated with more subtle signs, such as their wry humor; as when Jacob was explaining that the phone must be manned at all times, and when one of the authors asked what happened if he had to go to the bathroom and Jacob jokingly said he just "holds it" before explaining that the office phone line could be forwarded to a cell phone. As in any workplace, the dynamic varied depending on which two or three people happened to be working at the times of our observations.

When something happens that the operators may need to respond to, such as a car being stopped in the middle of the road, and they recognize it as such, the operators follow a notification/data collection protocol.

1) Create an entry in their own incident database and send a Tweet, often with a screenshot from the camera feeds with key items circled.
2) Copy the Tweet to the publicly-viewable travelers' information map, which has clickable feeds of many of the cameras (the older cameras, or the ones they pull in from the state DOT, will instead send out an image every thirty seconds or so rather than a live feed).
3) Depending on the severity and type of the situation, take other actions, such as sending an email to a listserv of city executives and other decision-makers (called the "executive text" even though it is usually read as an email); or calling inter- and intra-agency partners

requesting or sending information, such as informing the city's bus system that certain routes may be affected, or asking the state DOT to move their own cameras or send roadside assistance.

4) When an incident is no longer blocking one or more lanes, operators mark this in their incident database and their responsibilities are generally officially concluded. However, the office does send a weekly "incident of the week" report based on the actions generated during operations, and other teams in the city's DOT may perform analysis of the incident database for other purposes.

Of course, as we know from a great deal of work in CSCW [33, 34, 31], even the simplest protocols usually require customization and reinterpretation in the moment. In the next section, we describe one such instance in detail.

4 FINDINGS

In this section we examine the situated work of TMC operators in constructing and propagating situational awareness. In order to develop a sense of the work in the TMC, we first provide a detailed scenario encompassing many of the essential tools, processes, and concerns of TMC operators. The following section is a more directed examination of specific aspects of the operators' work and culture that support and facilitate the construction and maintenance of a situation.

4.1 An Example: Multiple Simultaneous Incidents with Escalation

Much of our observation time was spent in the midst of fairly brief, low key interactions such as managing fender-benders, and both these and more dramatic experiences influence our findings. However, occasionally our observation would be punctuated by periods of intense activity that helped add depth to the complexity of situational awareness in this field. The below occurred in the usually less busy middle of the day, over the course of about an hour, where multiple incidents had to be worked at once. As active incidents in the TMC are often denoted by the nearest intersection, we will call these the "2nd and Smith" and "James and Fountain" incidents. At this time, Harun and Zeke were working and senior operator Todd, and manager Jim were returning from a meeting.

Todd asks what happened while they were gone. Harun says that something had just come up at 2nd and Smith, and that there was construction. Todd settles in to his desk and looks at what Harun is doing. Todd: "I thought we were looking at the same cameras?" They briefly discuss an ongoing incident at Fountain street.

Commentary: The two of them are reasoning about what the other is seeing and what they should be watching—correcting a possible misalignment in shared use of the CMT. They use this tool to make sense of what is going on in the world, and they work together to make sure they get the most out of it. We discuss this in the context of the "tool schema" below in section 4.2.1..

Harun asks whether Todd wants him to "Tweet and TIM it?" (That is, share information about the incident on Twitter and the traveler information map.) After confirming their view and delegating these communication tasks, they problem-solve about camera views. Using these views, they discuss blockages and try to deduce which directions of travel are blocked. Harun seems to be interested in inputting public-facing information (putting in a second Tweet almost immediately after a previous one), while Todd focuses on the incident database (which is an Access database).

This incident seems fairly significant, with phone calls coming in and a great deal of stimulation. But that doesn't mean they can focus only on this incident: they co-delegate tasks as multiple incidents happen at the same time. Here their tasks seem to be divided more by system (Twitter, the database, etc.) than by incident. There are different strategies for dividing tasks that make for more effective situation maintenance. This shows how workplace awareness can support situational awareness.

A few minutes later, the phone rings, and Harun answers. The caller has conflicting information about the location of the incident. Harun, trying to figure out how the caller got their information, asks Todd if he sent out an executive text (and perhaps there was some incorrect information there). However, it turns out that Harun had put incorrect location information in the public travelers' information map: he used the *camera* location that they were using to watch the incident, not the actual intersection where the incident was happening. (Sometimes the best view is from a block or two away, or farther in the case of the high-mounted HD cameras.) Following this misstep, they are scrupulously careful to call out and verify information and actions. Harun also realizes from this conversation that the caller got emails when TIM was updated.

Harun asks whether Todd has called Maintenance & Operations (another unit of the city DOT) about the James and Fountain incident. He hasn't, and Harun volunteers to. After this the operators continue their negotiations. They also discuss whether an executive text should be sent out; ultimately they decide to because the incident is of the type "vehicle vs. pedestrian," which is a serious and politically sensitive category of incident.

There is a cost to sending out an executive text too readily: it invites a lot of attention from the executives, who might demand frequent updates and tax operators' attention further. On the other hand, if the executives aren't informed quickly enough, they may seek other, less credible sources of information, which has had serious negative consequences. The operators know they are an important component of executives' development of SA, so these decisions can be quite fraught.

Harun volunteers to notify Metro, the county transit authority, about what's going on, though he's not entirely sure *which* incidents he should tell them about. Todd as the senior operator explains that they should be notified if the incident is in a place where their buses go or if the traffic would affect their bus traffic. Despite all the excitement, Zeke has been embroiled in his other work, hardly glancing at Todd and Harun.

Todd writes the executive text while Harun checks the shared email account on his own monitor from which the text is being composed; he checks that it's still a draft before it gets sent out (meaning it wouldn't have been sent while still being composed). Harun mentions they had a quick turnaround on the 2nd and Smith incident, the other main incident that was on the top right of the camera wall. The two of them reason about whether the James/Fountain incident is blocking westbound traffic. They also look at the camera showing this incident, trying to figure out whether the blue vehicle they can see on screen was the one involved (they did not see the collision itself). Harun asks Todd which RRT unit was dispatched and Todd says it's RRT3.

The roadside response team, which patrols downtown, offers assistance such as pushing vehicles off the road, setting up traffic cones, and closing lanes. The city has nine such units, and the TMC is in frequent communication with the RRT dispatch center, as they often have valuable on-the-ground information that's not totally derivable from watching camera feeds or reading the police CAD digest. The operators' understandings of and good relationships with groups like this are a part of

what we will call their jurisdictional schema, and this gives them a wider range of options to improve their SA.

Within a few minutes, the police car and fire truck that had been at James and Fountain are gone. Todd is investigating something new, and wonders whether what he is observing on a map pertains to the incident he's trying to locate. Harun says that a car visible on one of the cameras should not be facing the direction it's facing, so that's probably it. They discuss at what exit the incident is happening, and that should tell them which camera they should pull up.

Here is a case where their canonical sources of incident information aren't giving them specific enough coordinates to help them select the best camera feed through which to view the incident. We describe this "triangulation" aspect of what we call the operators' tool schema.

After a couple of minutes, Harun confirms what location to report; it's not at an exact intersection so that's made giving a location difficult. Todd goes on Google Maps street view to explore more continuously around that area, as Harun looks on. Harun identifies and points to the location on street view. They both note how "weird" this area is. They hear on dispatch that there might need to be an investigation at the Fountain incident, so it might last a while longer. Almost on cue, a couple of minutes later a woman comes into the TMC and announces she's the executive duty officer (EDO). This sort of intrusion is a bit uncommon, though certainly not unheard-of.

Evidently, she wants an imagery update on the James and Fountain incident. She also asks about injuries; Harun isn't sure but says he will call RRT. Harun makes a call and asks about injuries. Failing to get clear information, and a bit nervous at the presence of the EDO, he tells them to let him know if they find out more. He then reports that the on scene responders are waiting to see if they'll bring in investigators. That means there might be a fatality, but to consider it as "serious injury" for now. Harun then says that information will come out in the executive texts—perhaps a gentle attempt to reassert that that's the preferred form and tempo of communication.

The EDO somewhat apologetically says she's monitoring the texts, but that there are new requirements in place for talking to the mayor, so she thought she would just come down here and talk to them in person. They say, "No worries," and she leaves.

Here is a situation where there may be external protocols that their own communication processes haven't been able to catch up with yet. A grasp of other groups' processes and requirements is an input to their own understanding of the situation and how they can affect it, which we discuss below.

In no time Todd and Harun are already on to the next thing, talking about what lanes will be open on Battery Street as incidents unwind. Cars are leaving another incident and, while watching, they again try to figure out whether and how particular cars are involved: "That one was in the picture earlier!" As they are not allowed to record the video streams for privacy reasons, they must rely on their own memory or, if they've been taking screenshots for Twitter, images. After about fifteen minutes and a few more phone calls, Harun asks whether they should contact the EDO. Evidently the injuries were non-life-threatening; while normally a person being transported by ambulance would trigger a higher level of response, the injured patient was transported mainly because of her age, and there won't be an investigation.

The debate on whether to call her back hinges on certain technicalities about the medical protocol for this case: they want to be thorough and do a good job, but they also don't want to communicate to the EDO outside of executive texts if it's not necessary. They must take stock of their approach to communicating with all sorts of outside entities, because those entities rely on them and because

those entities' actions influence the situation. We describe this below as being part of how they help create appropriate SA in others.

After a few more minutes, Harun and Todd discuss why a white truck they're seeing on screen can't move. Harun, offering commentary, says they should just put cones out so the other vehicles can pass. They briefly talk about how bad it is when people are injured in these incidents. Harun, probably sensing the researcher's observation is drawing to a close, says, "That was a good series of events!" Todd chimes in in agreement, saying nothing much happened the day before. Even when things get hectic, the operators find the fast pace stimulating and interesting.

4.2 Constructing Situational Awareness

From the foregoing example of a taxing and complex situation, we can see many behaviors of interest, which we will now discuss and expand upon. In this section, we describe skills and knowledge operators must develop, maintain, and transmit as both the receivers and transmitters of situational awareness. We begin with a (non-exhaustive) description of schemas operators develop around the resources available to them for their skillful action, then examine some of their practices in making use of these schemas and other skills to construct situational awareness. We will see how this comes together in their packaging of their own SA for other parties. We also discuss the social skills—as opposed to the technical skills or knowledge—operators use to help them maintain SA in their workplace.

4.2.1 Tool schema: capabilities and gaps Operators manage traffic using a variety of tools, which they learn to use and understand over a period of time. Many of these tools shape the awareness they are able to develop concerning the situations they manage. Their prescribed SA tools are: the CMT, the partially redacted CAD digest from the fire and police departments, the ambient audible radio chatter from a radio interop, and occasional phone calls. Also, since the operators record a variety of actions and events related to ongoing incidents in their incident database, they can also use this database to keep track of what has happened (and what other operators have done related to the same incident). Attending to what others have done based on what has been recorded helps the operators avoid duplication of effort. This is reminiscent of the flight strips observed by Hughes, et al. [35], where an instance of an artifact allows operators to collaboratively "work" a task.

To the extent that operators can become aware of situations, that awareness is constrained by the tools they have available to them. These constraints operate on two different facets of information incompleteness. On one end, two operators (the typical staffing level) cannot fully take in all of the information available from the tools they use in their work. Even with the full use of the camera wall and their individual workstations, it is always possible that something important is happening that they are not currently watching on camera. Moreover, which camera is best to use in any given situation is *not* always the physically closest to the incident—camera position as well as its technical capabilities factor in (some have much more powerful zoom than others), so this is a matter of expertise rather than mere proximity. As in the situation we described, camera locations may also not correspond exactly to the lay of the land. To address these gaps, over time, operators build a rapidly accessible "mental map" of the city based on the 250 or so cameras they have access to. The more experienced operators have developed some familiarity with sites where incidents commonly occur as well the various vantage points of the cameras, and can therefore quickly suggest an advantageous camera when they hear where an incident is likely happening. This expertise helps operators navigate an

impracticable excess of inputs to their perception. With reference to Endsley's model, where "perception" comes first, our operators must first develop a good working sense of what tools can tell them *before* they can be truly effective in their perception. And because this learning happens slowly and the available roster and capacity of cameras can change, it is not a purely static quality antecedent to situational awareness, but by necessity an always-developing capacity. These cameras are their primary visual sensing apparatus, so their perceptual skill relates significantly to their skill in understanding and manipulating the cameras.

Conversely, their tools may present information but it may be incomplete or obscured. For example, a camera may be positioned in such a way that there are tree leaves partly blocking its view—a concern that specifically came up multiple times in our observations and interviews. The CAD display may also have important information either redacted, incomprehensible to non-law enforcement, or ambiguous. In this case, the operators' construction of their situational awareness involves not simply taking in information, but also coping with information that is incomplete. This requires existing knowledge of what the tools' capabilities and shortcomings are, else the operators would simply take the signals they are receiving as an unquestioned source of truth. One strategy they learn to use is inferring the additional information they need from available indicators. To be able to do this requires an adequate understanding of what conditions are usually like in the area around the camera. With the tree leaves example, an operator can sometimes infer relevant information from just seeing the general direction and movement of traffic between or around obstructions. If this deviates from what is expected, that means a traffic-relevant issue is in play. They may also follow one response vehicle with a camera and be able to infer certain characteristics of the incident from how it is moving and where:

> Sarah puts a new camera on the top left and moves it around and zooms in. It shows a fire truck with lights flashing. Over the next few minutes, she uses the camera to follow the fire truck's path. But she does not change the camera after the truck goes out of view.

Operators also frequently—so frequently it could be considered an informal standard operating procedure (SOP)—used non-official tools to *triangulate* information. Their understanding of the limits of the information provided by prescribed sources led them to compensate with "sources of truth" that have a lower validity according to SOP, but which are known to be useful in practice. The most common such tool in our observations was Google Maps, which they would use for several purposes, such as compensating for confusing location data on the CAD feed (and thus get a finer-grained sense of which cameras they should be using) or figuring out where congestion was happening. This was a key tool for the situation we discussed, where an incident occurred in a "weird" location not easy to describe with typical identifiers such as intersection or exit number. Such practices can, of course, become more concretized into protocol, such as when social media indicators are included in situation evaluation models in Corral-de-Witt, et al. [15]. However, this practice emerged naturally from the information needs of the situation.

To sum, rather than collecting and blending information from prescribed sources, operators routinely coped with and overcame some of the limits of these tools. This judicious and creative use of nonstandard tools was a key part of the expertise they developed, not a failure on their part. We call this combination of skills and knowledge the *tool schema* used to build situational awareness. This concept treats tools not as a given that produce complete sensory information

to be perceived, but as a powerful but imperfect capability people actively engage with to inform their perception and comprehension.

4.2.2 Jurisdictional schema: navigating ambiguous responsibilities Many of the classic studies of situational awareness take place in settings where the environment is high-intensity and rapidly changing, where incorrect action can quickly lead to enormous tragedy (air traffic control centers, emergency rooms, nuclear reactors). Though this is clearly important to understand and support, we suggest that part of what makes TMC operators' situational awareness interesting is not only the intensity of their field of work, but also the unique and ambiguous characteristics of their environment and sphere of responsibility. Successful co-articulation with other entities of the shifting, overlapping fields of work can be a significant contributor to successful incident response.

The official jurisdiction of the city's DOT is the city streets and a specific downtown tolled tunnel where the city and state DOTs share control. An incident happening along an interstate or state highway is technically the purview of the state DOT. However, in practice, there is a significant amount of gray area and tactical flexibility, which operators must skillfully navigate and use to notify others and call upon available resources. We call this their *jurisdictional schema*, and it influences the shaping of their situational awareness by establishing what is within their own purview of notification and how calling upon other actors (such as the state DOT, city police, or others, whose operational jurisdictions the operators must also roughly understand) can affect severity and duration estimates. This is just as much a part of their concept of the situation as the technical tools they use. For example, asking the help of a nearby state DOT roving response unit that has towing capabilities (or who has contractual connections to a well-resourced towing company—yet another sphere of coordination) can get a disabled car off the blocked lane and onto the shoulder very quickly. If this happens at the beginning of rush hour, it can be the difference between minutes and hours of congestion, and help avoid secondary incidents. Operators explained to us that they sometimes call up the police when they can see what's going on with a critical incident (such as a suicide watch) before it is called in by a civilian. We also observed operators and particularly the highly experienced manager Jim pushing information to the Metro bus authority, proactively helping them reroute, which can increase the capacity of the road system. In the incident described above, operators attempted to leverage and extend their knowledge of the Metro bus authority and communicate with them to ultimately promote the more efficient movement of bus traffic, and by extension, the reduction of congestion related to the incident. A certain interagency *esprit de corps* can arise when a major incident arises requiring everyone's participation, but not all resources can be shared at all times and relationships between agencies are not always entirely harmonious.

The ability to distinguish between jurisdictions of various responsible agencies and individuals is something learned over the course of an operator's tenure. One operator, who had previously worked as an operator in another state, related how the city he had previously worked in had a different division of jurisdictions between response agencies who would handle incidents inside and outside the city. The two agencies would not communicate with each other and one operated by phone while the other operated by radio. He contrasted this with the situation in Seattle, where there were different jurisdictions for state and city DOTs, and the agencies had somewhat better working relationships, due to the TOC manager having previously been part of the state DOT. The jurisdictions of the relevant DOT agencies (and their relationships with each other) were different, but the operator brought an understanding of the importance of navigating jurisdictions from his prior work in the field. Understanding how

labor was divided amongst different parties, and how those responsibilities were negotiated between them, was a critical and nuanced understanding that operators had to build in order to do this work.

4.2.3 Incident qualification A crucial aspect of the operators' work is that of identifying (or, as we will call it, qualifying) an incident as something they should pay further attention to or take action on. This is a critical task for several reasons. One has to do with the extreme variety of phenomena they might happen to be observing. Unlike in many high-reliability organizations, where the potential for serious disaster is at the center of work practice, operators at the TMC are watching everything from absolutely mundane traffic to bridge collapses. Because humans, nature, and complex roadway systems are involved, events that start in one way can quickly evolve in another direction. That means there is no *a priori* differentiation for their perception that allows them to make a single decision about whether something is a "situation." Another is quite pragmatic: their attention and ability to respond are not infinite, so they must be careful to target their efforts appropriately. This involves both adherence to protocol and active sensemaking about the characteristics of the evolving situation. By coming together to articulate what the "situation" is from their shared operational and analytical perspective, they are helping to construct their own "common field of work" [30] and delineate where it overlaps with that of others.

When initially describing their qualification procedures, operators tended to give fairly simple distinctions: they needed to act when lanes were blocked on important roads within their jurisdiction (generally not highway roads, which were the jurisdiction of the state department of transportation). They would also keep an ear and eye out for apparently traffic-related issues on the CAD digest and radio chatter (paying attention to certain keywords like "lane blocking"), and investigate further. In practice, however, these decisions were more complex, in particular because although their protocols concerned specific actions and notification procedures, the choice of *what to pay attention to* was generally always a judgment call in the moment. It was an admittedly difficult task to determine when a non-event from their perspective would bubble up into something they should pay attention to. For example, we once observed the operators raptly watching a car fire happening in a parking lot and discussing what was going on. Usually, incidents happening inside parking lots were not relevant to the operators, who typically focus on issues blocking at least one lane of traffic. Their attentiveness was of course partly related to how dramatic and exciting the scene was, but it was also a case of something that, should it become a traffic-blocking issue, would likely need very fast and effective response. Knowing this required a sense of the *partner agencies' own protocols*, making use of their jurisdictional schema: the Fire department would probably respond to this situation, and Fire's protocols specified that they "take" (i.e., block) at least one lane. Then, by default, this would become a blocking incident.

Part of the value the operators provide is their ability to help prevent situations from becoming major incidents. We observed a great deal of *proactive monitoring* from the operators; being attentive to common causes and effects (such as growing congestion in key areas, problems with bus routes) and notifying parties that can take actions on the ground is of key importance in the operators' role. In this case, not all the important actions operators take may be captured in their incident database, and thus the ways their observations and decisions are converted into record-keeping are not consistent across the range of issues they attend to. The operators primarily take action by communicating in some fashion, and yet they and their agency partners have limited human capital and attentional resources. This means that their

situational awareness includes a strong working knowledge of *whom* to communicate with (who might be tactically most effective in the moment) and what *effects* that communication might have. They even keep a whiteboard in the TMC updated with who the current EDO and commercial vehicle contacts are, as this changes occasionally. Endsley would call this part of "projection" in situational awareness. Operators must learn that there is a diffuse and hard-to-predict causality in the roadway system, and small differences can compound quickly into large messes.

A further complication is that not all potential situations bubble up to the level of requiring intervention. Highly effective operators, who have developed effective collaboration with other agencies, can prevent "situations" from arising in the first place. A tire in the road may be handled by roving RRT units before it causes a wreck (and this may be observed by operators watching the nearby camera feed, without any action being needed on their part). Importantly, not all of these "pre-situational" interventions are captured in the routine collection of incident data operators undertake via the incident database, but they are a part of the general awareness and organizational effectiveness of the operators and their partners.

4.2.4 Simplification of tasks via implicit and explicit coordination Typically there are two operators working at a time, and this is considered preferable to a single operator. One might be tempted to think that introducing another party into the response process would make following the necessary steps in the right order more challenging. However, especially when there were multiple incidents, we observed the opposite:

> Harun explains that incidents do not come in simultaneously…it's all about coordination and claiming tasks and asking other people to do things. Working together for a while means that they can do these things without thinking about them too much. Zeke pipes up that there's also a lot of work coordinating with other agencies; that sometimes people come up for a conference, and it can include not just [the state DOT] and the mayor's office, but also Metro and even the traffic engineers (changing the signal timing, for example). I ask if more operators ever get called in for these big incidents because it's gotten too crazy. Harun reflects for a moment, and says that no, usually two operators can handle just about anything.

Operators accomplish this with a combination of explicit (verbal) and implicit (nonverbal) coordination; in our relatively short observation time we saw many pairs of operators coordinating in a variety of styles. Perhaps due in part to the relatively small number of operators, we observed a much more individualized set of practices for informal coordination than Heath and Luff did when observing London Underground operators; these strategies did not stand apart from individuals, but were based in part on chemistry and synergy between individuals.

If there are multiple incidents happening at once, there are different ways of dividing tasks: one operator can "own" an entire incident; one operator can do the same type of task (e.g., writing tweets) across multiple incidents; an operator can take whatever the next available task is after he has finished his current task; or any number of other configurations. Although there are protocols for handling an event in general, the TMC has no established, pre-determined protocols for dividing tasks between operators, even though effective coordination during an incident can be the difference between success and disaster. As such, we were able to observe a variety of task division patterns among the operators.

In particular, here, the operators need to be not only aware of what the others are doing in their shared work environment, but predict the likely trajectory of their work mate's actions

within the protocol. Sometimes they can do this implicitly and sometimes it requires explicit discussion, particularly when there is a breakdown or near-breakdown. This is the sphere of more standard CSCW understanding of "awareness" as in, say, Hornecker, et al. [25], who describe awareness as "facilitating implicit coordination, anticipation, and assistance, and simplifying communication. When there is high awareness, little verbal communication is employed in coordinating activity. Actions build upon each other effortlessly and seamlessly. … We describe these as *reactions without a request.*"' We observed a bit of this disintegration of accurate implicit coordination in the episode described above, where a small error led to quick adjustments to process in the moment. Gutwin, et al.'s aspects of workspace awareness, particularly Extents, Abilities, Sphere of Influence, and Expectations, were harnessed for this work as well.

We should note that just because there is no single identified protocol for task division does not mean operators have no sense of who should be doing what. Once an incident is underway and a pattern of task sharing has emerged, expectations for that pattern can be revealed when someone misses a step. For example, when a bus was disabled on the roadway (also an example of jurisdictional schemas, because the buses are operated by the county-level transit authority, but can quickly become a shared issue), manager Jim apologized to operator Sarah for not having already done a task even though there had been little to no previous outward discussion about task sharing:

> Jim: 'I probably should have called M&O about that disabled bus.' Sarah says she can do it; she makes a call and tells them what traffic it's blocking. Jim apologizes and Sarah says it's no problem.

This component of awareness informs an operator's *situational* awareness because it can change the trajectory of what she is paying attention to, and thus where perception is targeted. Taken as an aspect of their shared situational awareness, this awareness forms part of the structure of the situation, and clearly must be adequately shared between all the people taking part in tasks.

4.2.5 Situational awareness as an information product Operators must not only make sense of the unfolding situation, determine what (if any) role they should play in handling it, and bring together a wide and sometimes ambiguous collection of resources, but also inform others about the situation in a timely but measured manner. Thus their work often takes the form of articulation work [31] for other parties, such as travelers or executives. This, in effect, means that they help inform the situational awareness of other parties. In trying to do this responsibly and effectively, they must consider a range of factors: how often is too often to update messaging? How vague or precise should this information be? What kinds of decisions will the message cause the recipient to be able to make? Does the information need to be placed spatially in a particular way (such as DMSs on the roadway)? With whom and how should this messaging be coordinated? And what impacts will this messaging have on the behaviors of others, which will then, of course, shape the situation itself? All of these decisions and more lead to the key outputs of the operators' work. The operators are sensitive to these questions, and connect them not only to information transmission, but the other goals of that transmission. When asked in interviews about what the term "situational awareness" meant for them, they called attention not only to their *own* ongoing and incident-specific awareness constructed "piece by piece", but the situational awareness they were able to support in others as well:

Todd:

> I think being situationally aware is being cognizant of what is going on: listening to the scanner, constantly browsing our CAD aggregator, looking up at the video feeds, especially at the bridges because sometimes those break and we don't know about it until it is too late or there's a huge backup. So being aware of those things. Also, monitoring our Twitter feed because we do get alerts from citizens. Their reports aren't necessarily called into the police so things like that we have to constantly monitor. We also need to make sure that we are providing accurate information on our DMS signs because sometimes someone might forget to turn off the signs and we could be saying "there's a crash" when there really isn't, so we just need to be aware of the things that we're putting out to make sure that what we put out is correct and accurate.

Harun:

> And personally, I think we bring in like situational awareness...we look at the situations we digested and then we notify, disperse information amongst everybody. Make sure everybody knows and, outside of that, just clear up the incidents. So we kind of just help everything flow...keep flowing. [later when asked for a definition of SA] I think situational awareness is...like here we have a standard protocol for how to deal with things. But um, for situational awareness, I guess it is just, for me, is getting an understanding of a situation in order to make the biggest impact towards resolving it. So, when you understand the problem, like holistically, and you know, kind of trying to come up with a solution, like piece by piece.

The main camera wall is an example of how the operators produce channels of situational awareness for others. Most of the time, operators are using their individual workstations to browse, view, and manage the camera feeds and dynamic message signs. Since much of the work is collaborative, this would suggest that the large, configurable camera wall would be a key tool for shared attention and collaboration between operators. However, while operators do sometimes point to or look at the camera wall when coordinating with each other, the camera wall is more typically configured to serve the information needs of *others*. Our participants explained how they organized what was being displayed on the camera wall as a sort of continuous executive summary of the most pressing traffic issues, which people (often at a higher level in the organization) who walked into the TMC could quickly grasp. The different areas of the wall typically contain the same general types of information: some problem intersections on the lower left for the use of traffic engineers, some of the movable bridges (which can quickly bottleneck if they malfunction) in the top right, and a feed of the state DOT's primary camera in the top left. The "executive texts" that are sent out to inform city executives about serious incidents must be created with care, because the attention of the executives is even more at a premium than their own in some ways. So in a sense, the operators must act as one of the sensing tools used by these other entities.

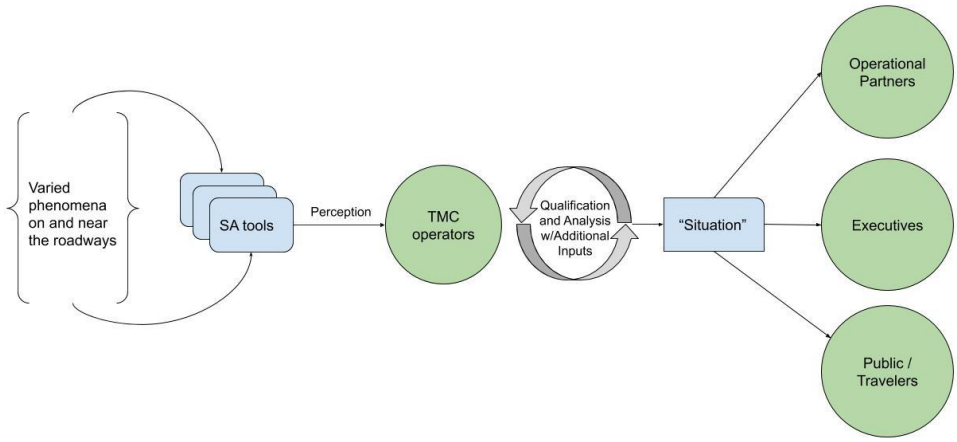

Figure 2: Information flow from real-world phenomena to TMC information customers.

Members of the public are also recipients of this SA. This comes partly in the form of cautiously worded Twitter posts. Indeed, this is their primary method of broadcasting information to the public, but their approach is largely the opposite of the process undertaken by Vieweg, et al. That is, the operators try to stay within a very neutral, structured format to give appropriate information about current situations without veering into commentary. Sometimes they are intentionally vague because of shared jurisdictional issues (the Fire department, which also tweets about its incidents that often overlap with the TMC's, should be the only one giving specific information about medical hazards, for example). They do gather information from the public on Twitter (as mentioned by Todd above), as it is a unique and timely channel for possible intelligence, but it is never considered high-quality information until it is verified or triangulated with canonical sources. In that sense, the situational awareness they create via these messages is intentionally constrained, in part because other official channels are responsible for other aspects of the relevant information. Dynamic message signs (DMSs), and traveler information map posts; and very rarely, emergency alerts are other genres with their own physical limitations and considerations (e.g., DMSs are only visible to travelers currently passing by them, which means they are already traveling and likely have a destination in mind, so guidance is required). The information operators transmit to the public is informative, but also sometimes persuasive, as when DMSs urge people to avoid certain areas. To do this work properly, the operators must hold two different conceptions of "traffic" in their minds: as a kind of fluid flow that they help manage, and as a collection of individuals they are trying to inform and persuade.

4.2.6 Social supports to the maintenance of situational awareness Previously we have been discussing how situational awareness is constructed and produced. However, this work can be demanding upon the individual and collective attention of the operators. We observed that they make effective use of informal social dynamics in order to help them properly maintain this attention, and such practices constitute an important part of the overall situational awareness effort.

Operators in the TOC know that the pace of work can change instantaneously. One moment, the main city roads could be running smoothly and in the next there could be a multi-car pile-up blocking thousands of residents. Because these dramatic turns of events happen so quickly,

and there is much to learn from these incidents, the operators have developed unique aspects of workplace culture that help them maintain attention and practice a sort of "active recovery"[2] to recharge during slow times. Although attention is (arguably) an individual cognitive phenomenon, it can be supported via social strategies. Some of the strategies we observed were reinforced informally, even humorously, and were a consistent part of the work culture. While any workplace will have informal dynamics that have some relationship with the work to be done, we though it important to complement the largely technical and knowledge-oriented descriptions of the TMC's SA work with some discussion of these dynamics, as they point to the very *situatedness* of SA, and our descriptions of how SA is achieved would be incomplete without them.

Operators need to remain attentive enough to perform the critical work quickly. One way they do this, curiously though, is through what could be called superstition. All operators know that situations can evolve rapidly, so they have co-created an ongoing superstition that prolonged low-activity times precede a high intensity incident. They openly speak about "what could be coming", which keeps their attention focused even during lulls in activity.

Before we even began our observations in earnest, operators would jokingly warn us not to use "the q word". When we asked what the "q" word was, they leaned in close and whispered, "quiet." This word embodies the cultural superstition we are describing. It is seen as taboo to use the word because it might will incidents into existence. In one surprising instance, senior operator Todd used the term without fear, saying he kind of liked having things going on. However, shortly thereafter, he ruefully noted: "So right after I said the 'q word,' three incidents happened. I was asking for it I guess." Though they do not literally believe that calling the overall situation "quiet" is a curse that will cause incidents to happen, it is a nod to the unpredictability of phenomena in the complex system of the city's roadways. Even good current situational awareness—that of an "all systems normal"—can be a temptation toward complacency. As Nofi [36] explains, situational awareness is a very time-bound thing and can go from excellent to nonexistent in an instant.

It is impossible to maintain a state of high attention during all slow activity times. We found that storytelling played a unique and important role in helping operators actively recover after periods of high intensity. We often overheard operators trading stories of bizarre, complex traffic incidents that arose and developed in unexpected ways. Because the operators rotate shifts, they often have new stories to share with their co-worker. They would also return to a number of "old favorites" that they liked to discuss. Notable incidents included tanker truck rollovers where bizarre materials (fish guts, feathers, frozen crab, even bees!) would spill out, making it harder to clear up or even requiring a hazmat response. In some stories, the incident was simple, but the response was complex, such as when a wreck occurred on a hill but the response team had a hard time approaching it due to slick material on the road. These stories were often given a nickname (usually the cargo material or location) and became part of the lore.

The operators enjoyed recounting these incidents and cracking jokes about them. They would even pull us—as observers—into these storytelling moments. Sometimes, if both operators knew about the incident, they would enthusiastically tag-team to tell us the story. This was clearly an enjoyable part of their job that reinforced the idea that roadway chaos could ensue at any moment. It also served another important role–knowledge management. The

[2] https://campusrec.wfu.edu/2019/10/active-recovery-and-how-it-benefits-you/

operator's oral storytelling practices were continuous case-studies for the operators to learn from and "pass on" to those who are new to the TOC. New operators could get a sense of the different ways a situation could evolve before having to deal with an emergency firsthand, and benefit from experience specific to the work of traffic operations. We found ourselves drawn to this practice, often returning to campus and sharing incident stories with other co-authors.

In sum, cultural maintenance of attention and oral storytelling were a key part of maintaining situated awareness at a *social* level. If we think of distributed or team situational awareness as requiring some overlap or compatibility in what people are actually perceiving and understanding, then it might also be useful to understand what they do to keep each other focused and prepared to perceive.

5 DISCUSSION

Although some work in CSCW seeks to promote situational awareness, the concept has not yet been fully explored empirically or theoretically. From our study, we have illustrated that situational awareness is *constructed* by operators via a variety of interlocking schemas for their own decision-making as well as to provide it to others. Moreover, it plays multiple roles in the context of the work group; informing decision-making, yes, but also focusing shared attentiveness, and establishing and maintaining relationships with other teams and entities, among others. In a 2000 review of situational awareness theory and research, including her own, Endsley [37] describes how mental models developed over time can influence SA in the moment: "In this sense, SA, or the situation model, is the current state of the mental model. For example, one can have a mental model of a car engine in general, but the situation model (SA) is the state it is believed to be in now (e.g. it has a given RPM, it has a given level of fuel, it is at a given temperature, etc.). This situational model captures not only the person's representation of the various parameters of the system, but also a representation of how they relate in terms of system form and function to create a meaningful synthesis —a gestalt comprehension of the system state." While expert domain understanding is important, we have shown some of the ways other types of schemas allow operators to blend a variety of understandings to construct SA "piece by piece" and package it for others. In so doing, they participate in the creation of a common field of work for everyone participating in the incident.

We have seen from the foregoing discussions that situational awareness combines many phenomena of interest to CSCW, and CSCW's own analytic sensitivities can contribute measurably to the growing multidisciplinary understanding of this complex construct. And although the term is sometimes used in underspecified ways, it *is* used, and that usage has consequences we should pay attention to. For example, Lucy Suchman's recent report [38] on lethal autonomous weapons (LAWS) claims that automated systems cannot possess the qualities necessary for an accountable situational awareness that humans can. That is, based upon international humanitarian law's "principle of distinction" (the rule of ethical warfare that prohibits indiscriminate targeting), the aspect of situational awareness in which an agent distinguishes between a legitimate combatant target and anything else in the world can't be accomplished by a non-monitored non-human system. Her own starting point for defining the term stems from its military context. She ultimately seems to claim via her arguments about LAWS that SA is a state, quality, or accomplishment unique to human cognition; or else that the unpredictable variety of the context of warfare means that adequately training an autonomous agent to obtain the "awareness" needed to make this critical distinction is extraordinarily unlikely. In our own study, human judgment calls, synergies based on established relationships,

and intuitive know-how all contributed to the construction of SA. These combinations of knowledge, skill, and on-the-ground reality are assembled differently in each situation; the relationships between people, phenomena, and tools allows us to analyze responsibility in a way missing from automated or fully *a priori* models (see for example Latour's [39, p. 177] relational assessment of people and guns). CSCW's access to this kind of information from ethnographic observation should become a key voice in the development of situational awareness technologies.

Endsley's model of situational awareness distinguishes between "situation(al) awareness" and "situation assessment." Assessment is the process by which people create situational awareness, and it's affected both by the perceptual tools people have and individual cognitive factors. Yet the "awareness" is, in this model, a cognitive state that is promoted by other processes she has called "situation assessment." What we observed was a concomitant "awareness about awareness" that helped operators refine and improve their SA in the moment and better transmit it to others. Such awareness was not purely delimited by individual factors but equally by shared resources and sensemaking. At least in multi-jurisdictional, public facing work settings, any understanding of situational awareness must place the tool schema issue in focus, because operators do not simply absorb all sensory data coming from an unmediated world. We observed that the tools the operators have mediate the "world" they have access to and thus what is possible to be "aware" of. The more experienced operators are not only more fluent in using the tools, but as the data being provided by the tools is a proper subset of all the possible information they might receive, also have a strong sense of what the limitations are and what other data points can help fill the informational gap. A gas truck bursting into flames on an overpass has a single physical reality, but regardless of how dramatic and impactful that reality is, it is never one single "situation." What type of sensor or surveillance tool is being used to monitor the event, who needs to know about aspects of this physical reality, and how it should be acted upon are all highly contextual and open to interpretation. Of course, it is a common move in CSCW and other interdisciplinary areas to say that seemingly straightforward phenomena are contextual and open to interpretation, but the value of this particular case is that we have seen specific examples of these contexts and interpretations; and actions within these contexts may not be fully derivable from any particular description of a physical reality, but they do act to produce reliable and coherent results and meet general expectations for performance. Moreover, operators will ideally maintain some model of *others'* situation models (influenced by these others' own tool schemas and incident response protocols), so as to know how to call upon them as a resource or provide effective information for them. This model shapes the realities of incident response in very tangible ways. Research on shared situational awareness has shown us that not all entities need have the same awareness for the SA to "count" as "shared," but this study points to the need to better understand how *multi-agency* situational awareness might be better understood, and how recursive "awareness of other groups' awareness" contributes to it.

This study also shows how distributed/team situational awareness can work in practice when there are multiple partially overlapping groups with partially shared goals. Our operators undertake their tasks of packaging information and making requests for resources in the context of a broad, complex jurisdictional schema. This "awareness" of context helps them better to produce the meta of the "situational awareness" they must obtain from themselves and provide to others. Our own observations did not take place at a high-reliability organization (the traffic management operators we observed typically mitigate existing situations and do not

have purview over major catastrophes), but we did observe various strategies operators used to help them maintain this strenuous awareness of the road system and the evolving impacts of traffic-related incidents.

How might we better support robust and flexible situational awareness for operators like these? First, our observations revealed some of the extent to which "perception" is shaped and constrained by tools and jurisdictional issues. Further work might assist by helping operators map out jurisdictions and more proactively assess what the gaps in tools and shared responsibilities are. Such a project would require the kind of careful ethnographic observation that helps us understand longer-term processes of learning and development. On a more theoretically robust level, using the concept of common fields of work might help us understand the structures of distributed situational awareness, or showing which resources are currently shareable by different non-collocated groups. Finally, since CSCW's analytic lens can be quite broad and sustained in observational style, it can help offer new ways to address the ever-challenging questions around assessing SA and whether or not it is ultimately "successful."

With these complexities in mind, we are better suited to take more accurate and thorough empirical accounts of situational awareness construction. We can also better assess the growing suite of tools being developed to create automated situational awareness tools for traffic management (we believe the concept may hold in similar domains). Since decisions about what to attend to are situated in the moment's individual context, tools that use machine learning to support situational awareness should be cautious and measured in the kinds of claims and decisions they make on behalf of human operators—they are not using entirely the same data and heuristics as human brains, so they should be very transparent and communicative about their reasoning. The interplay between creative, intelligent human awareness and the non-human systems that multiply human cognitive power is an object of key interest to distributed cognition research. Machine learning applications that seek to enter this distributed system should therefore help to strengthen the analytic and intuitive power of the people involved, not gradually weaken it by making decisions too fast and simple. Future machine learning applications might innovate by exploring the hard problems around how complex organizations conduct multiway conversations that dynamically construct multiple situational awarenesses for different stakeholders. Smart cities with a form of "system SA" can use these schema concepts to query a wider range of useful information from automated and human sensors. Learning from operators' tool and jurisdictional schemas to identify the different configurations of awareness that are likely to be needed connect to domains of interest to CSCW and organizational studies—relationships between shifting organizational and social structures and operational output—and are also a challenging but promising field for machine learning in an increasingly networked and interdependent world.

6 CONCLUSIONS

In this study, we have examined how operators in a large city's traffic management center make use of their schemas of tools and jurisdiction, and shared cultural resources, to effectively construct situational awareness for themselves and those they communicate with. We have shown how operators gradually develop their expertise to allow them to articulate the nature of the shifting fields of work involved in traffic management.

We claim that any tools to support situational awareness informed by CSCW principles must not only provide information to the right agents, but also support the fundamental ontological-epistemological multiplicity and dynamism of "the situation" itself. What counts as

a situation is not driven exclusively by a priori qualifications or data structures, but dynamic configurations of people, tools, organizational structures, and processes. People dynamically shift their frames of reference based on their experience, and situational awareness tools that aim to actually improve situational awareness must not serve as a replacement of but an enhancement to experience.

CSCW could both benefit from and contribute to more direct engagement with the construct—with its unique perspective on the intertwining of technical systems, sensemaking, and intensive collaboration, it can help to move the technology forward in a holistic, integrated way.

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