Technology-mediated macrocognition: Investigating how physicians, nurses, and respiratory therapists make critical decisions

Ying Ling Lin [a,b], Jessica Tomasi [a], Anne-Marie Guerguerian [a,b,d,e], Patricia Trbovich [a,c,f,*]

[a] Institute of Biomaterials and Biomedical Engineering, Faculty of Engineering, University of Toronto, Toronto, Canada
[b] Interdepartmental Division of Critical Care Medicine, Hospital for Sick Children, Toronto, Canada
[c] Institute of Health Policy, Management and Evaluation, University of Toronto, Toronto, Canada
[d] Faculty of Medicine, University of Toronto, Toronto, Canada
[e] Neuroscience and Mental Health Research, Hospital for Sick Children, Toronto, Canada
[f] Research and Innovation, North York General Hospital, Toronto, Canada

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ABSTRACT

Purpose: Although intensive care clinicians are expected to make data-driven critical decisions using the technologies available to them, the effect of those technologies on decision-making are not well understood. Using the macrocognitive framework, we studied critical decision-making and technology use to understand how different specialists within teams make decisions and guide the development of decision-making support technologies.
Materials and methods: The Critical Decision Method was used to understand the macrocognitive processes used during critical decision-making of twelve critical care clinicians. Deductive (based on the macrocognition framework) and inductive coding were used to analyze the macrocognitive processes, their interrelationships, and their relation to technologies.
Results: Over 60% of critical decision-making macrocognition was devoted to Sensemaking, Anticipation, and Communication. The most technology-mediated process was Sensemaking. Of particular note, physicians and respiratory therapists extracted information for their own use, while nurses extracted information to communicate to others. Physicians switched between ten macrocognitive processes, whereas nurses and respiratory therapists switched between five processes.
Conclusions: This exploratory study provides much needed details about the different ways in which specialists use technologies to support decision-making tasks, particularly those involving sensemaking, which are essential to the design and development of decision-support technologies.

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1. Introduction

Pediatric critical care comprises a large potential for patient harm as it is a complex socio-technical environment in which teams of clinicians must continuously monitor data, scattered across multiple technologies, to care for critically ill patients. Multi-disciplinary team care requires clinicians integrate the multiple data streams with their own and their colleagues' specialist knowledge. Data Integration and Visualization Technologies (DIVTs) have been developed to help integrate data (e.g., heart rate on the physiological monitor) and information (e.g., clinical notes organized in the Electronic Medical Record EMR) but these technologies represent data in fundamentally different forms than traditional, raw numerical data or seconds-long waveforms [1]. Consequently, despite the development of DIVTs to help streamline

and alleviate the burden of "big data", clinicians continue to experience cognitive overload, misinterpret data, and mistrust signals leading to suboptimal patient care or worse, patient harm [2-4]. The lack of effectiveness of technology in supporting clinician decision-making is attributed to the fact that these solutions don't fully support the mental activities that must be successfully accomplished to perform a task. To better design these decision support technologies, we must first understand how expert clinicians, under hurried and stressful conditions, make accurate, life-saving data-driven decisions. To support efficient data-driven decision-making, this exploratory study aims to characterize the cognitive processes used by clinicians during decision-making and to identify the technological sources they access and how they use them. With the influx of technologies into clinical environments, we require an understanding of the mental activities/cognitive functions used during decision-making so that we can better support clinician decision-making. Otherwise, incorrect assessments and misdiagnoses may persist until they become apparent through resulting patient degradation.

* Corresponding author at: Institute of Biomaterials and Biomedical Engineering, Faculty of Engineering, University of Toronto, Toronto, Canada.
E-mail address: Patricia.Trbovich@utoronto.ca (P. Trbovich).

Terms

Abstraction   An understanding of a concept that cannot be directly measured or understood in concrete terms.

Critical decision method   A type of cognitive task analysis method that investigates how people make critical decisions.

Macrocognition   A set of cognitive processes that characterize how people think in natural (non-laboratory) settings.

Compound macrocognitive processes   Macrocognitive processes found to occur in parallel but does not preclude other macrocognitive processes or their simultaneous occurrence.

Technology management   A macrocognitive process occurring in sociotechnical systems with a high prevalence of technologies, often requiring users to actively manipulate multiple technological interfaces and components, to perform cognitive work.

Naturalistic decision-making (NDM) is the term used to describe decision-making in the real-world settings, under situations of time pressure and uncertainty [5]. Macrocognition describes cognitive processes occurring during NDM [6,7]. It is used here to understand the skills and strategies used by intensive care clinicians when they perform tasks using multiple sources of patient data.

Critical decision method (CDM) is used to extract expert knowledge when making high-risk decisions in complex situations [8-10]. Macrocognition is the study of mental processes used during complex cognitive activities. [11]. The macrocognition framework contains the following *primary* macrocognitive processes: Naturalistic Decision Making, Sensemaking, Planning, Adaptation, Problem Detection, and Coordination [6]. *Supporting* macrocognitive processes are: Maintaining Common Ground, Developing Mental Models, Mental Simulation and Storybuilding, Managing Uncertainty and Risk, Identifying Leverage Points, and Managing Attention [6]. Schubert, et al. used this framework, as a set of nine processes, to understand the differences between novice and expert decision-making in emergency medicine [12]. The macrocognition framework has also been used to analyze the effect of care management on primary care practices [13]. We applied the macrocognitive framework to understand how clinicians make decisions in intensive care using technologies.

2. Materials and methods

2.1. Study design

The critical decision method was performed using semi-structured interviews with physicians, nurses, and respiratory therapists as they recalled when they had to make a critical decision during an incident. To deepen the understanding of the process leading to the critical decision, the timeline of the incident was revisited several times to elicit information related to assessment parameters and salient cues surrounding the critical incident. Participants were encouraged to describe the cognitive processes involved in their clinical judgment and the data and information sources used (e.g., colleagues, patient assessment, monitoring devices, therapeutic devices, documentation technologies) to make a decision during the course of the incident.

2.2. Setting

Interviews were conducted in clinical office spaces located either near or within the participants' Intensive Care Unit (ICU). As schedules between physicians, nurses, and respiratory therapists (healthcare practitioners providing cardio-respiratory support) varied, choice of location was based on clinician convenience.

2.3. Participants

Twelve participants, of which four were physician intensivists, four were registered nurses, and four were respiratory therapists, participated in this study. All participants were equivalent of full time staff and were from the same pediatric ICU. Each received a $50 gift certificate for their participation in the study.

2.4. Procedure

The expert knowledge elicitation technique (CDM) was applied in one-hour semi-structured interviews conducted in June and July of 2014. A researcher trained in interviews asked participants to recall a situation where they made a critical decision. Probe questions were based on those from Crandall's original CDM and those modified by Baxter, et al. [10,14]. Supplemental questions also prompted recollection of the sources of data and information (i.e., colleagues, patient assessment, monitoring devices, therapeutic devices, or documentation technologies) deemed relevant to their decision-making processes. Sample probe questions can be found in the appendix. Interviews were audio recorded, de-identified, and transcribed verbatim. Research ethics approval was obtained from the clinician participants' hospital (SickKids Hospital REB #1000045483).

2.5. Data analysis

2.5.1. Macrocognitive processes coding

Transcribed interviews were coded using NVivo version 8 software for 1) macrocognitive processes and 2) sources of data and information. Two reviewers (YL and JT) coded interview transcripts deductively based on a priori macrocognitive processes identified from Klein's original macrocognition framework and Schubert's subsequent modifications to that framework, inductively based on emerging processes identified. Raters reviewed their inductive codes for overlap (i.e., both raters may have identified the same emerging process principle, but needed to come to consensus on the wording moving forward) [6,12]. Coding discrepancies were discussed among the coders (YL and JT) and principal investigators (PT and AMG) until consensus was reached. The set of agreed upon macrocognitive processes comprised the "analytical framework" that was used by the coders to independently code subsequent interviews. Cohen's kappa for inter-rater reliability was calculated using NVivo's coding comparison query function. Landis suggests that a kappa between 0.41 and 0.60 provides moderate inter-rater agreement [15]. Once inter-rater reliability was above 0.4 on four independently coded transcripts, the remaining eight were coded by one coder (YL).

2.5.2. Data and information sources coding

In the ICU, data and information were sourced from colleagues (e.g., clinical knowledge), the patient (e.g., their work of breathing), and technology (e.g., vital signs on the physiological monitor, infusion pumps, dialysis machines, extracorporeal, membrane oxygenation technology, EMR), see Appendix. Specifically, technology sources were any monitors detecting and displaying vitals, other physiological parameters, or organ support data. These technologies influenced macrocognition by providing data that clinicians perceived and used to make decisions. To deconstruct this broad category, sources of data and information, specifically the medical devices and software, were coded according to the code list found in the appendix.

To understand how one macrocognitive process interrelates with another (compound macrocognitive processes) during critical decision-making, matrix queries were used. The matrix query function of the NVivo software returns the frequency of two nodes (codes) located close together in the transcribed interviews. The function has been used to find paired relationships and was applied in this study to identify macrocognitive process pairs [16,17]. Here, the macrocognition process

pairs occurring within a given paragraph in the transcript reflect the sequence of macrocognitive processes within a clinician's line of thought. The frequency of the paired occurrence was normalized using their respective proportion in each specialist macrocognition distribution. In this study, paired relationships were identified using a 50% cut-off rate of the maximum normalized value, within each clinical specialty.

3. Results

3.1. Study participants

Table 1 shows the participant demographics. There was an equal number of physicians, nurses and respiratory therapists and an equal distribution of senior (five years or more experience) and junior staff (under five years of experience). Half the participants were fellows and active in both the cardiac critical care and pediatric (medical-surgical) intensive care units. The other half of the participants were staff and specialized to a single intensive care specialty.

3.2. Inter-rater reliability

For a sample of four interviews, the unweighted average inter-rater reliability of coding of macrocognitive processes and sources was 0.43. According to Landis and Koch this is considered adequate [15].

3.3. Macrocognition processes

There were 2405 verbal references related to 10 macrocognitive processes. Table 2 presents the definition, number of verbal references and percentage of each process. Across all three disciplines, the ranking, by highest proportion of verbal references, of the macrocognitive processes were similar with Sensemaking, Anticipation, Interprofessional and Interteam Communication (subsequently referred to as Communication), accounting for approximately 60% of all macrocognition. Fig. 1a shows similar ranking of macrocognition processes across specialties. Interestingly, physicians and respiratory therapists exhibited an equal distribution of macrocognitive processes and devoted 34% of macrocognition to Sensemaking. The main processes of nurse macrocognition were evenly distributed: Sensemaking (23%), Anticipation (18%), and Communication (20%).

3.4. Macrocognitive processes as a function of sources of data and information

The distribution of data and information sources among all macrocognitive processes, is shown in Fig. 1b. Overwhelmingly, technologies were used during Sensemaking. Physicians attributed 57% of technological sources to Sensemaking while nurses attributed 32%, and respiratory therapists attributed 51%. Table 3 characterizes how each specialty executes each macrocognitive process with sources of data and information used.

Table 1
Demographics, years of experience, specialization.

		Physicians	Nurses	Respiratory therapists	Total
Number, (n)		4	4	4	12
Gender, (n)	Male	2	0	1	3
	Female	2	4	3	9
ICU Experience, (n)	≤5 year, fellow	2	2	2	6
	>5 years, staff	2	2	2	6
ICU Specialization, (n)	CCCU*	1	1	N/A	2
	PICU**	1	3	N/A	4
	PICU/CCCU	2	–	4	6

* CCCU: Cardiac critical care unit; ** PICU: pediatric intensive care unit; N/A: not applicable; respiratory therapists in this ICU department serve both the CCCU and PICU.

Table 2
Macrocognition process codes, adapted from Klein, et al. and Schubert, et al. [6,12].

Macrocognitive process	Definition	Number of verbal references and proportion (in %)
Sensemaking	Deliberate, conscious process of fitting data into a frame	667 (28%)
Anticipation	Anticipate how a situation might unfold, see potential problems or needs of the patient, team, and unit, and adjust plans and actions accordingly	394 (16%)
Interprofessional and interteam communication	Communication and coordination with the ICU team and across internal and external services	390 (16%)
Technology management*	Process of troubleshooting problems arising from the function of technology or the management of multiple technologies used in a given situation	199 (8%)
Managing attention	The use of perpetual filters to determine the information a person will seek and notice	190 (8%)
Time management	Skill of anticipating how long things take and how timing affects patient care	146 (6%)
Managing uncertainty and risk	The use of skills for coping with uncertainty which may arise from missing data, from data whose validity is unclear, from ambiguity over competing situation assessments, and from complexity that interferes with sensemaking	136 (6%)
Problem detection	The ability to spot potential problems at an early stage	129 (5%)
Self-awareness and self-management	Awareness of own knowledge, capabilities, and vulnerabilities	80 (3%)
Managing complexity	Track and manage multiple patients with complex conditions while attending to family needs, the healthcare team, and organizational and systems requirements.	74 (3%)

*Indicates a new macrocognitive process.

Physicians assessed stability of each physiological systems while nurses assessed overall patient stability (or instability) and respiratory therapists assessed respiratory system stability. For Sensemaking, all clinicians relied on the patient manifestation (i.e., how the patient looked). Physicians and nurses then relied on the physiological monitor as the main technological source of data. Sources for respiratory therapists, beyond patient, were the physiological monitor, interventions including mechanical ventilation, blood analysis, respiratory system-related imaging, and other colleagues.

For Anticipation, physicians predicted possible interventions or illness progression while nurses and respiratory therapists predicted the protocols required to execute physician-directed treatments. Physicians used technologies to "extract" information while nurses and respiratory therapists manipulated technologies to monitor or administer treatment (e.g., set audible alarms on physiological monitors, set infusion rates on pumps, manipulate ventilator settings). Also, for the process of Anticipation, nurses and respiratory therapists mentioned colleagues as sources of information, suggesting they often plan with other team members.

For the process of Communication, physicians and respiratory therapists extracted information for their own use (e.g., to make decisions about medical interventions or mechanical ventilation) whereas nurses extracted information to subsequently update colleagues away from the bedside. Colleagues were the most relied upon source of information during the patient's stay and no single technology mediated interprofessional communication. Physicians did not report use of the EMR for interprofessional communication while some nurses (2/4) and respiratory therapists (2/4) did.

Technology Management involved layers of data verification with nurses taking charge of the initial data validation and physicians
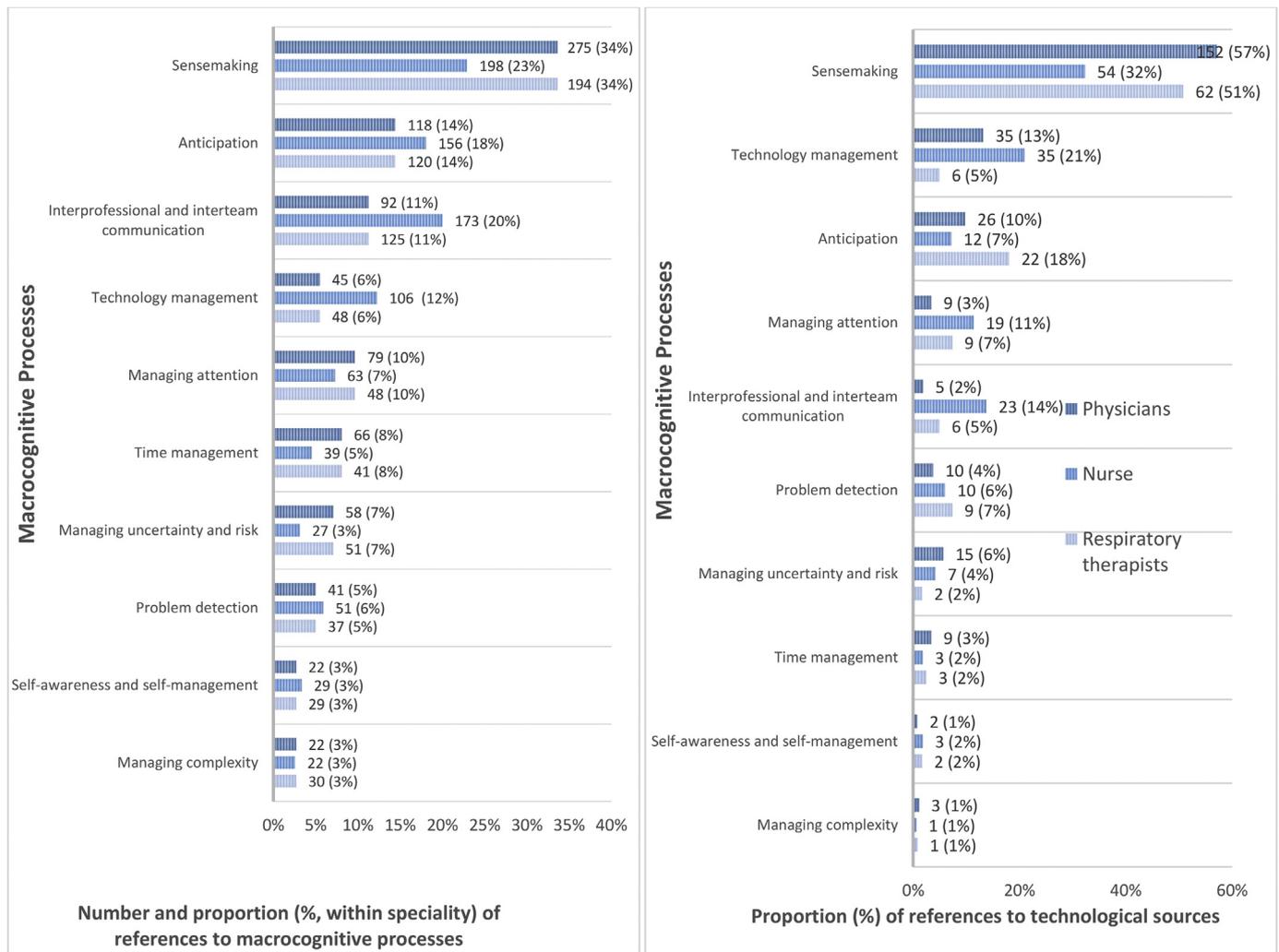
Fig. 1. Breakdown of macrocognition, within specialty, according to process type and technology intensity. a) Distribution by number of verbal references and percentages, within specialties, of macrocognitive processes b) Distribution of technological data sources among macrocognitive processes, within specialties.

conducting a subsequent validation when critical decisions were required. Physicians and nurses both mentioned the physiological monitor and its importance for cardiac monitoring but differed in how they would troubleshoot dubious data. For example, physicians would refer to telemetry for detailed cardiac readouts whereas nurses would plan for additional leads for a more reliable cardiac reading. Respiratory therapists managed ventilation related technologies.

Each specialty differed in how they Managed Attention (i.e., selected and monitored the most important data and qualitative information). Physicians managed multiple patients at once and paid particular attention to "critical" patients or aspects of patient health that were deteriorating. Nurses paid attention to small changes in patient deterioration. Similar to physicians, respiratory therapists managed multiple patients but prioritized monitoring based on changes in respiratory deterioration. For Managing Attention tasks, physicians reported relying mostly on colleagues while nurses and respiratory therapists reported that they primarily relied on the physiological monitor and the patient. All other processes (Time Management, Managing Uncertainty and Risk, Problem Detection, Self-Awareness and Self-Management, and Managing Complexity) were minimally technology-mediated.

3.5. Compound macrocognitive processes

Due to the dynamic nature of macrocognition, processes often occur simultaneously [6]. We analyzed how a single macrocognitive process lead to

another and illustrated their interrelatedness in Fig. 2. Interrelationships, or macrocognitive pairs, are shown as double-sided arrows between boxes. The relative strengths of relationships are the values labelled on each arrow. Processes with strong relationships (i.e., above half of the maximum normalized frequency value, within each group) are shown on the map and those with relatively weaker relationships are absent from the map. The similarity matrices, normalized output from the matrix queries, for all possible pairs of macrocognitive processes are found in the appendix.

3.6. Physician macrocognition structure

For physicians, all ten macrocognitive processes were interrelated in some combination, as illustrated in Fig. 2. Problem detection was the central macrocognitive process and was related to five other processes. A suspected problem may trigger closer monitoring, understanding the problem in context, anticipating further tests or therapies while minimizing uncertainty in the data. The high degree of interrelatedness between all processes suggests that physician macrocognition was the most distributed among the three groups and that they shifted frequently between processes during critical decision-making.

3.7. Nurse macrocognition structure

Nurses had five paired processes and five unpaired processes (absent from map). Managing Complexity was central to their

Table 3
Macrocognitive processes and associated sources of information or data. Data sources are ranked according to proportion of respondents with number of references in parentheses.

Physicians		Nurses		Respiratory therapists	
Characteristic	Example(s)	Characteristic	Example(s)	Characteristic	Example(s)
Sensemaking Systematically reflect on the different organ systems and then seek out necessary data or order the required tests or monitoring devices.	"I was trying to work out what was going on, what phenomenon did I have that could explain all of these clinical findings, and then would just systematically try to go: OK this is the heart problem? What tests should I do for that? This is the brain problem? What tests should I do for that?"	Physically examine the patient and use their knowledge to conclude patient stability.	"[W]hen you have a very sick patient you're not only looking at all the technologies that the patient is hooked up to, but I have to look at my patient as well."	Gather data primarily from the patient and from the detail of the waveforms from mechanical ventilation support.	"[I]nspiration looks a certain way, expiration looks another way, there are times when you see certain alterations in the waveforms that are difficult to explain. For instance, you can sometimes see prolonged exhalation, where you wouldn't expect it."
Main sources		Main sources		Main sources	
1. 4/4 Patient [12] 2. 4/4 Physiological monitor [11] 3. 4/4 Blood analysis [9]		1. 4/4 Patient (31)/Physiological monitor [17] 2. 2/4 Interventions [10]/Blood analysis [7]/ECG [4]/EMR [3]/Parent [2]		1. 4/4 Patient [24] 2. 3/4 Physiological monitor [23]/Interventions [15]/Blood analysis [11]/Imaging [8]/Colleague [4]	
Anticipation Foresee the patient's response to therapeutic (surgical or medical) interventions or illness progression.	"No, it was predicable because we introduced a new medication that may contribute to this."	Use their experiences to mentally simulate the possible scenarios and plan for possible interventions the attending physician would order.	"I was getting blood [requisitions] out so we could get some more blood up and the doctor came and I said, "we need some blood. The[n] the doctor says, "Give a unit right now, give it a unit." So, we did that and then I went over and got the racks and [I] said, "Do you want some more blood?" He says, "yes, yes I want FFP."	Plan for escalation, de-escalation or duplicate replacement technological respiratory support for critically-ill patients.	"Once you're in a low [ECMO circuit] flow state and there's a clot within the circuit we already knew […] the whole [circuit] can fail." "I remember one child that they described, it almost sounded like it was a twin."
Main sources		Main sources		Main sources	
1. 3/4 Blood analysis [7]/physiological monitor [6] 2. 2/4 Imaging, ECHO [4]/intervention, ventilation [4]/ECG [2]		1. 4/4 Physiological monitor [6] 2. 2/4 Colleagues [6]/Imaging [2]		1. 3/4 Intervention, ventilation [12]/Patient [6]/Colleague [3]	
Interprofessional and interteam communication Collect data and information from the bedside team or the previous multidisciplinary team.	"We would constantly talk about our goals […] and what were the problems with this patient."	Select and relay data and information based on their colleagues' speciality.	"I won't tell the surgeon that [the pH has changed]. He wants to know if they're draining. From the surgical side, if there's any wound problems. He might come in [to] look at the drugs. He'll want to know if we had to escalate on *epi* [nephrine]."	Delivery of ventilation support to multiple patients means they rely on colleagues' respiratory specific summaries that highlight important patient details. They are the most prone to losing context when changes are made.	"[PEEP has] been changing and you're […] not sure why it's been changed, whether it's a colleague, a fellow RT, has put it up and not put [why] anywhere in the chart, or your doctor's come in and put it up because they've caught [it] before you've caught it and they haven't had a chance to tell you yet that it's gone up."
Main sources		Main sources		Main sources	
1. 4/4 Colleagues (32) 2. 1/4 EEG [2]/Patient [1]/Blood analysis [1]/Dialysis circuit [1]/Imaging [1]		1. 4/4 Colleagues (44) 2. 2/4 EMR [5]/Patient [3]/Physiological monitor [3]		1. 4/4 Colleague [22] 2. 3/4 Patient [4] 3. 2/4 Intervention [3]/EMR [1]/Physiological monitor [1]/imaging [1]	
Technology management Troubleshoot or combine with confirmatory technologies seemingly faulty data if they detect a problem during analysis of that data.	"If you really want to see the rhythm, then you have to go to the full disclose telemetry [to] be able to see how it transitions, but a shortcut using the [bedside] monitor is to go to the graphical trend [and] see how the heart rate transitioned."	Take responsibility for the validity of data collected from most bedside monitoring technology and are first to troubleshoot or confirm readings before communicating it to colleagues or committing to the EMR.	"If you notice that the three leads [ECG] now looks weird and [is] obviously not normal for the patient, I'd call the physician and then we would do a 12-lead [ECG]."	Take responsibility for the respiratory support technologies and carry out orders to escalate or reduce support. A primary goal is to wean off the support technologies, especially invasive ventilation.	"Investigations [helped us] realize that there were software upgrades that could be done on our homecare ventilator [which] allowed us to see waveforms on the ventilator [that] we didn't have before."
Main sources		Main sources		Main sources	

Table 3 (continued)

Physicians		Nurses		Respiratory therapists	
Characteristic	Example(s)	Characteristic	Example(s)	Characteristic	Example(s)
1. 4/4 Physiological monitor [7] 2. 3/4 Imaging [4]/Blood analysis [3]		1. 4/4 Physiological monitor [12] 2. 3/4 ECG [3] 3. 2/4 NIRS [6]		1. 2/4 Interventions [3] 2. 1/4 Physiological monitor [2]/EMR [1]	
Managing attention					
Prioritize patients based on the subset ICU population(s) they belong to or criticality of illness based on amount and type of support technologies and, at the patient-levels, organ systems-based issues and seeking data or information currently missing by prescribing orders.	"There's always one or two patients that will take more of my attention or more of my time"; "I focus on the things that are problematic just for that patient." "your goal should be to focus on what are the things that I can't afford to miss?	Constantly watch the patient and look for the abnormal values that fluctuate beyond thresholds. Values which fit the pattern of "normal" will not be given as much attention. They divide their monitoring attention with timely delivery of interventions.	"I don't worry […] if I see normal results, that's good. I focus on what's not going right." "the priority obviously is the patient and making the interventions that need to be done within five minutes."	Monitor for the escalation of respiratory support or episodes of desaturation signals patients of increased concern.	"Generally, if there's a particular patient who's been acting out maybe desaturating all night, maybe they've progressed from room air to BiPAP and they're going to get a tube. I think we're probably going to have some problems with that patient, and they're definitely indicated."
Main sources		Main sources		Main sources	
1. 3/4 Colleague [4] 2. 2/4 Interventions [3]/Imaging [2]		1. 4/4 Physiological monitor [12] 2. 2/4 Patient [8]/NIRS [3]/EMR [2]		1. 2/4 Physiological monitor [8] 2. 1/4 Patient [4]/Colleague [2]/blood analysis [1]	
Time management					
Carry out initial assessments followed by periodic reviews to efficiently update the status of multiple patients. These reviews entail foreseeing effect of interventions, illness evolution or estimated time of hospital-based processes.	"[B]ecause we were so focused on instantaneous changes, we were actually [obtaining] blood gases in the unit [since] RTs […] giv[e] us the print out much earlier than [if the blood gas results] would have appeared on [the EMR through the central lab].	Schedule interventions and coordinate them when they are at different intervals. The interventions range from bedside care to out of unit care, including surgeries and discharge, and always involve documentation.	"Feeds were less than two and a half hours, we're feeding him every three hours and so it wasn't enough, but he was waking up exactly half an hour before a feed." "This hour I'm preparing my medications, I'm starting the feeds, I've got to document."	Manage scheduled patient visits and calls to the bedside. When de-escalating from invasive ventilation, RTs may encounter unforeseen complications requiring them to re-organize their patient load and travelling between patients.	"You can go anywhere from half an hour to two to three hours before [the patient is settled]. Maybe not solid for three hours, but you're back and forth in there most of the time just trying to get them settled."
Main sources		Main sources		Main sources	
1. 2/4 Blood analysis [4]/Colleague [2] 2. 1/4 Interventions [1]/EEG [1]/EMR [1]/Physiological monitor [1]		1. 1/4 Physiological monitor [2]/Colleague [1]/Patient [1]/Blood analysis [1]		1. 1/4 Physiological monitor [2]/Colleague [1]/Blood analysis [1]	
Managing uncertainty and risk					
Decrease uncertainty and risk by increasing and selecting data and information.	"You increase your level of monitoring [by] doing blood work much more frequently, […] doing assessments much more frequently to try [to] anticipat[e] what's going on."	Decrease uncertainty of abnormal data by combining with patient assessments.	"You're assessing [whether] this is an accurate reading on the monitor […] by palpating the pulse [to check if it] matches."	Gather information from bedside nurses relative to respiratory function. Patient assessment will involve auscultation of the lungs or drawing blood for gas analysis.	"[A] good indication if they're not happy and they're not settling [is] auscultation. They've completely decreased [and] have collapsed [on one side of the lungs] but their [oxygen saturations] are fine."
Main sources		Main sources		Main sources	
1. 4/4 Imaging [7] 2. 3/4 Patient [5] 3. 2/4 Blood analysis [2]		1. 2/4 Patient [4]/Physiological monitor [3] 2. 1/4 ECG [3]/Colleague [2]/imaging [1]		1. 2/4 Colleague [4] 2. 1/4 Patient [1]/blood analysis [1]/EMR [1]	
Problem detection					
Combine data and information from bedside staff to identify problems.	"This is where the ECG and the CVP come into effect, it became clear that something had changed and the patient was having, now clearly differently a dysrhythmia. Heart rates that had come down to normal, 150 s, 160 s, now back up again to 170 s, 180 s, but not sinus anymore, a clear arrhythmia that's associated with this type of surgery."	Focus on patient vitals and appearance but pay close attention to subtle fluctuations of values if trending negatively.	"Desaturation shouldn't happen this frequently[..] I actually had to intervene because I saw her fluctuating a little bit around [the lower target threshold], but it was fluctuating but heading down."	Focus on specific vitals and blood gas indicators related to oxygenation, patient's overall appearance and use of muscles for breathing, and the level of ventilation support.	"Over the course of the night they had a slow increase in the amount of oxygen they needed and occasionally were dropping their saturations more than normal and listening to them they were getting a little bit quicker just like their lungs sounded different but not necessarily significantly different but just a little bit different."

Table 3 (*continued*)

Physicians		Nurses		Respiratory therapists	
Characteristic	Example(s)	Characteristic	Example(s)	Characteristic	Example(s)
Main sources		Main sources		Main sources	
1. 3/4 Physiological monitor [4] 2. 2/4 ECG [3] 3. 1/4 Colleague [1]/patient [1]/Blood analysis [1]-/Interventions [1]/NIRS [1]		1. 4/4 Physiological monitor [5] 2. 3/4 Patient [5] 3. 1/4 ECG [3]/Interventions [2]		1. 4/4 Physiological monitor [6] 2. 2/4 Patient [6]/Intervention, ventilator [2]	
Self-awareness and self-management					
Reflect on how they feel when faced with uncertainty regarding patient care or team management.	"[When you have] a very sick patient with multi-organ failure but without knowing the cause you can't target the therapy. So, that makes you feel very uneasy."	Develop personalized strategies to manage their responsibilities.	"If I forget anything [during handover], it's usually the first 10 min driving [after my shift]. And then I pull over and then I call. [O]nce I tell, I'm finished."	Keenly aware of their specific domain knowledge and will seek help from other specialties to enable them to focus on the respiratory aspect of patient care.	"I quickly decided that we probably need some extra help. […] I can't manage the patient and manage the problem with the ECMO circuit."
Main sources		Main sources		Main sources 1/4 Colleague [2]/Patient [1]/Intervention, ECMO [1]/Physiological monitor [1]	
1. 2/4 Colleague [2] 2. 1/4 Patient [1]/ECG [1]/Physiological monitor [1]		1. 1/4 Physiological monitor [1]/Intervention [1]-/Imaging [1]			
Managing complexity					
Trust colleagues and parents to handle monitoring tasks to then focus on different patient aspects or different patients requiring their more urgent attention.	[If] they're stable [then] some patients' parents take care of them while they're in the unit and they don't get monitored at all, the parents follow the monitoring and we see them once every 12 h. So […] we tailor the monitoring [by] how sick or potentially sick the patient is.	Gatekeepers to the patient for the coordination of different services ordered. They facilitate parental involvement in the ICU.	"[When] parents are […] staring at the monitors I often push the monitor away or turn it to the side [to help them focus on their child]."	Being highly mobile and with high patient loads, rely on the bedside team or other colleagues to coordinate patient care in cases where there are other urgent situations.	"It's challenging when you're trying to be in three places at once which becomes hard, which is where you're relying on so many […] to get things done."
Main sources		Main sources		Main sources	
1. 2/4 Colleagues [2]/ 2. 1/4 Parents [2]/Physiological monitor [2]/EEG [1]		1. 1/4 Parent [1]/Patient [1]/Physiological monitor [1]		1. 1/4 Patient [1]/Intervention, ECMO [1]	

macrocognition since it involved managing direct patient care while attending to the family, the ICU team, organizational and system requirements. This process was related to reducing uncertainty of data (Managing Uncertainty and Risk), selecting and monitoring the most important data and qualitative information (Managing Attention), and balancing with scheduled interventions (Time Management). Sensemaking, Anticipation, and Communication, processes with the largest proportion of macrocognition (i.e., 23%, 18% and 20%, respectively), were absent from the macrocognitive maps, suggesting that they did not consistently relate to any other process.

3.8. Respiratory therapist macrocognition structure

Respiratory therapists had seven process pairs and five unpaired processes. Uncertainty and Risk Management was the central process with four interrelated processes, suggesting they use the interrelated processes to minimize risk and uncertainty in the data. Technology Management was absent from the map which suggests this process was carried out separately. For example, in a complex situation where a patient was on high circulatory support (e.g., Extracorporeal membrane oxygenation or ECMO), the respiratory therapist decided to concentrate on fixing the ECMO circuit.

4. Discussion

This study adds to the literature by describing the cognitive processes used by intensive care clinicians when making critical decisions. Results showed that the most common macrocognitive processes used by three intensive care specialties (physicians, nurses, respiratory therapists) were Sensemaking, Anticipation and Communication. All clinician specialties relied heavily on technology during Sensemaking. Technology Management was a macrocognitive process elicited more often by nurses than other specialties.

The interrelatedness of the set of 10 processes in the physician macrocognitive map suggests a constant shift between processes during critical decision-making. Nurses and respiratory therapists, however, reported fewer interrelated macrocognitive processes with half of processes exhibiting weaker interrelatedness (i.e., absent from the map). Unpaired processes may act as singular, cognitively intense processes or may be linked to physical work (e.g., going to find extra electrodes for 15-lead ECG tests). Understanding differences in the use, and patterns of use, of macrocognitive processes across specialties can have important implications for emerging Data Integration and Visualization Technologies (DIVTs). It is imperative that DIVTs be designed to support and enhance the cognitive processes for decision-making. Otherwise, such technologies run the risk of leading to incorrect assessments and misdiagnoses. Our results suggest that physicians require DIVTs that support frequent process switching while nurses and respiratory therapists require DIVTs that support one specific macrocognitive process at a time. Furthermore, the relatively singular execution of macrocognitive processes may indicate a higher proportion of physical, direct patient care associated to nurses and respiratory therapists work compared to the indirect patient care management by physicians.
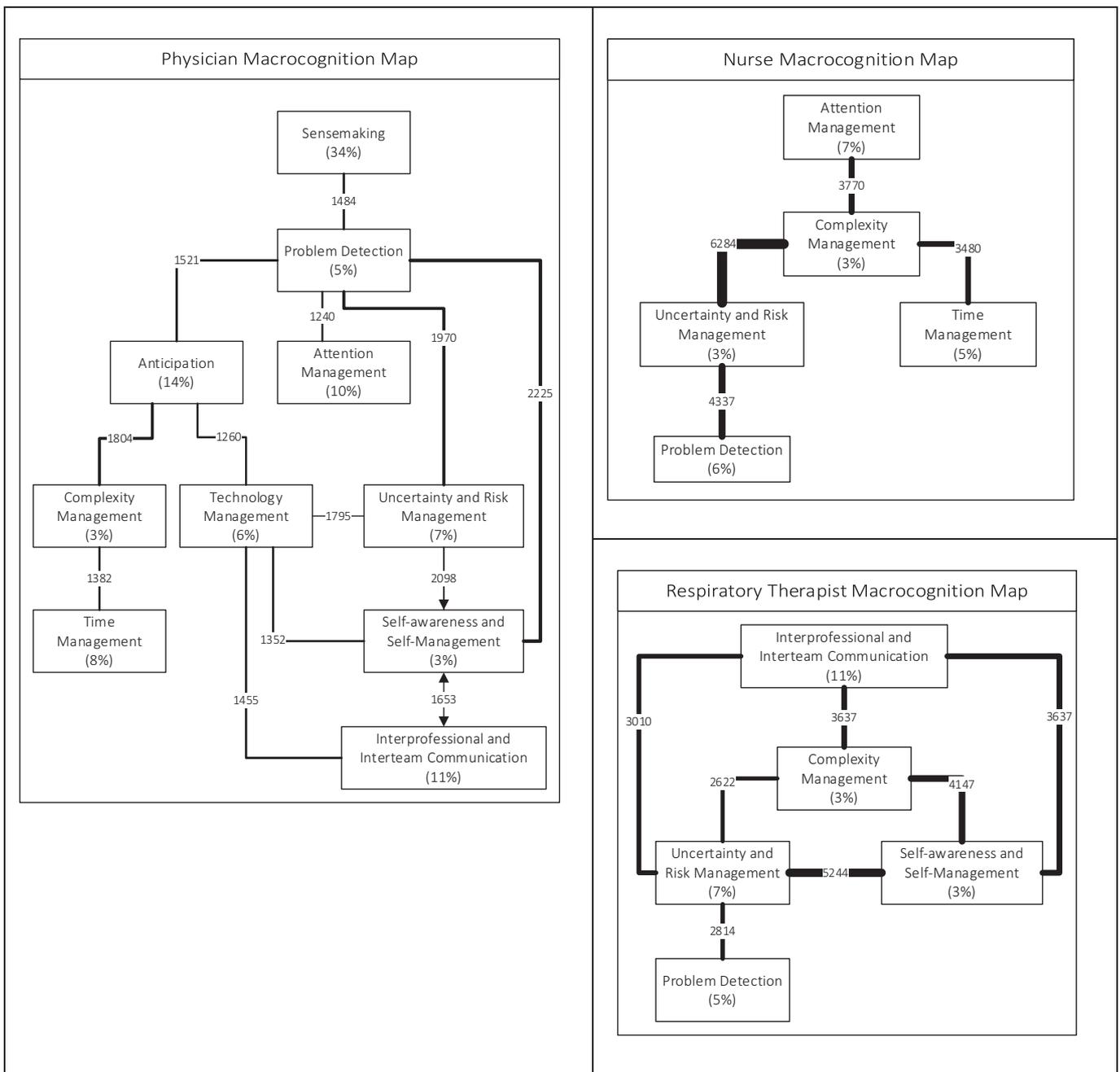
Fig. 2. Macrocognitive maps of physicians, nurses and respiratory therapist during critical decision making. Relationships between macrocognitive processes in intensive care for a) physicians, b) nurses and c) respiratory therapists with strength of relationships indicated by the number on the double arrows and the line thickness.

4.1. Implications for DIVT design to support macrocognitve processes

Our results are consistent with other finding indicating that clinicians routinely access the physiological monitor, intervention technologies (e.g., ventilators, organ-support technologies), blood analysis results, and imaging [18]. Therefore, the integration of these four types of medical devices should be prioritized if ICU managers and/or DIVT designers wish to reduce clinicians' data search efforts. In addition, the various levels of data and information abstraction (e.g., cellular to hospital-level services) employed by each specialty supports the notion that technology should reflect an abstraction hierarchy, a natural organization of data and information (e.g., abstracting from the cell processes of the patient to high-level whole systems) [18-21]. DIVT interfaces at the bedside should be designed with consideration of

nurses' ranked information needs, their routines/protocols, and their most common macrocognitive processes [22,23]. Similarly, DIVTs should be designed for physicians and respiratory therapists when they are away from the bedside.

Since physicians and respiratory therapists are responsible for multiple patients and consequently cannot be at each bedside, they are prone to observing the evolution of each patient on a broken timeline. These two groups could benefit from technologies which fill-in the data trend picture. Physicians and respiratory therapists reported recognizing long-term fingerprint-like patterns in the data, for example in the ECG or ventilator waveforms, respectively. Nurses, operating in an instantaneous timeframe, reported detecting subtle changes in patient manifestation. Given the different needs of the three clinical specialties, facilitating patient typification,

parametric data trends, and qualitative information trend should be incorporated into future DIVTs.

All three specialties exhibited a common macrocognition pair of (Problem Detection)(Managing Uncertainty and Risk). The consistent relationship between these two processes may stem from incomplete or missing data characteristic of fragmented data and information eco-system (i.e., disparate technological sources of data such as multiple medical devices crowding the patient bedside). In practice, clinicians must repeatedly verify the values which do not fit their predicted patient trajectory. As such, technologies used by all team members should prioritize this chain of macrocognitive processes.

4.2. Implications for team macrocognition

Holtrop, et al. used the macrocognitive framework to understand changes in team care (care management) by relating the support of macrocognition processes to facilities with successful outcomes [13]. They found that practices that were conceptually aware of macrocognitive processes and had explicit procedures to facilitate those processes were more successful [13]. For example, "Sensemaking and Learning", a single macrocognitive process, was supported by structured staff training (e.g., Lean method for quality improvement) [13]. Similarly, DIVTs could support team decision-making if they explicitly addressed macrocognitive processes, especially those found to be highly dependent on technological information sources. Processes which were less technologically-mediated, including Time Management, Self-awareness and Self-management, and Managing Complexity may benefit from institutional policies and procedures.

Institutional policy could support Time Management and team Sensemaking. For example, in the minutes or hours following a clinician's official shift, a nurse stated: "*If I forget anything, it's usually the first 10 minutes driving. And then I pull over and then I call. […] so I immediately tell. Cause once I tell, I'm finished.*" A downtime or protected time to hand over key information should be built into the work flow thereby ensuring clinicians have sufficient time to transmit data and information between shifts. DIVTs supporting communication between teams could be designed to include last minute, off-site annotations that flag important information from off-duty staff to on-duty staff. In the short-term, facilitating team Sensemaking in this case could potentially benefit from procedural solutions.

A notable study by Nemeth et al. was their use of the macrocognitive framework to design a software system that would support individual and team cognitive work and communication in the burn ICU (BICU) [24]. They used the macrocognition framework to identify the cognitive processes and subsequently developed a model for BICU cognitive work. The proposed technology could then be designed to support any of the functions of the model. Our study increases our understanding of the macrocognition of three primary clinical specialties and provides direction for prominent macrocognitive functions in tandem with the advancement of DIVTs.

5. Limitations

The main limitation is the use of only the CDM, an inherently biased, self-reported account of the incident and the decision-making process. Future studies would benefit from using supplemental methods to triangulate and substantiate findings.

In the Canadian intensive care setting, respiratory therapists are a separate clinical specialty and they contribute distinctly to multidisciplinary decision-making. In other settings, the role of respiratory therapist may be fulfilled by physicians or nurses who undertake responsibility for respiratory therapy which may impact the types of macrocognitive processes used and the generalizability of our findings.

Future studies using the CDM for intensive care settings could narrow to one of the macrocognitive processes (e.g., Sensemaking), intensive care sub-specialties (e.g., physicians), or patient populations/

domains (e.g., post-cardiac surgery neonate monitoring or post-traumatic brain injury monitoring). Analysis of a shared critical incident experienced by all specialties could reveal more subtle aspects of the dynamics of team macrocognition for decision-making.

Another limitation was the distribution of clinical specialties. The variance in clinical specialty between cardiac critical care and intensive care (medical-surgical) resulted in a skew to more expertise in the cardiac care domain. Through interviews and unpublished observations, we found that cardiac patients are monitored for more parameters than medical surgical patients. In addition, some technologies are specific to cardiac care or to medical-surgical units. It is recommended that future studies separately assess the macrocognitive processes used to care for cardiac critical care patients versus medical surgical patients.

Despite the study data having been collected five years ago, from the time of writing, we believe the results remain relevant as ICUs exist at various levels of data integration and DIVTs continue to be implemented in ICUS. Our results provide much needed details about the different ways in which ICU clinicians use technologies to support decision-making, which are essential to the design and development of future DIVTs. We acknowledge that the EMR landscape continues to mature and the industry as a whole is moving towards optimization of EMRs and developing new healthcare technologies. Consequently, the relationships between clinicians macrocognitive processes and technologies will inevitable vary as a function of the types of technologies used. That being said, our findings related to the types of macrocognitive processes used by clinicians during critical decision-making, performed using information technology or without any technology at all, can be applied to the engineering of any information technology designed to support decision making. If we design information technologies based on incorrect or incomplete understanding of clinicians' cognition, we run the risk of designing technology that degrades performance rather than improves it. Thus, our findings are relevant to the continual evolution of the EMR landscape. ICUs vary in terms of integration of data, and many ICUs may very well still be reflected in this study.

Macrocognition maps, here used as an analysis technique, illustrate the interrelatedness of macrocognitive processes and could supplement other cognitive load measurements (e.g., NASA-TLX) [25]. However, it was derived from subjective recollection. To reinforce findings, it may be supplemented with objective measures of data source use (e.g., video recording of the incident, log of EMR consultation).

6. Conclusions

This study introduces the concept of technology-mediated macrocognition and characterizes its component processes. Findings highlight how the contemporary ICU environment remains highly multimodal and fragmented, and emphasizes the need for data integration from all available sources. Physicians, nurses, and respiratory therapists differed in how they use macrocognitive processes during critical decision-making tasks. We suggest insights to guide data integration and visualization through technologies, policies and/or procedures to support macrocognitive processes most prominent to each discipline.

Conflict of interest

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jcrc.2019.06.002.

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