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Review

Resilient performance of emergency department: Patterns, models and strategies

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A B S T R A C T

Emergency Departments (EDs) in the U.S. have long experienced difficulties in meeting the often-unexpected healthcare demands resulting in widespread overcrowding. Understanding performance adjustment in such complex systems would inform initiatives to improve ED resilience to expected and unexpected demands. Resilience Engineering (RE) literature offers abundant case-based findings that highlight performance adjustment in ED practices. However, there is a lack of effort to generalize such findings into a harmonized knowledge base. By reviewing and summarizing findings from literature, this study first presents four patterns of performance adjustment: Adjustment by Matching, Extending, Sustaining, and Transforming. Second, five conceptual models of resilience are presented from the literature exhibiting different characteristics of resilience in EDs. Third, in order to support ED practitioners in coping with the chronic safety issues, this paper provides a repertoire of resilience strategies to manipulate four ED resources: staff, supplies, space, and sequence (four S's) that can facilitate performance adjustment. As the synthesis of such findings, the patterns and strategies are incorporated into each model. Strengths, weaknesses, and recommended usage for the ED resilience models are also discussed. By inspiring a transition from a case-based approach to a model-based approach for resilient healthcare, the findings of this paper provide an initial framework for developing better work strategies and new tools to deliver safer and more productive ED practices.

1. Introduction

Emergency Departments (EDs) in the United States (U.S.) have faced a recent crisis in maintaining high quality of care due to an increase in the demand for emergency care and a decrease in the availability of EDs (Institute of Medicine, 2007). Take for instance the State of California: between 1994 and 2014, total annual ED visits increased by 27.8% whereas the number of EDs in the State decreased by 18.3% (Hsia et al., 2018). The ED crisis has been largely driven by legislative acts such as the Emergency Medical Treatment and Labor Act (EMTALA) of 1986, which requires hospitals to admit any patient regardless of financial ability. This mandate forces hospitals to risk providing care without compensation (McDonnell et al., 2013). In addition, increased costs of specialized services (e.g., computed tomography, lab-testing) have added further economic pressure on EDs (Pitts, 2012).

The imbalance between supply and demand of ED care has resulted in widespread overcrowding (Boyle et al., 2012; Trzeciak & Rivers, 2003) a phenomenon where the number of patients and associated treatment needs exceed the available resources such as medical staff, equipment and physical workspace (Moskop et al., 2009). On the one hand, overcrowded EDs have commonly experienced patient boarding (i.e., patients held temporarily in EDs) and ambulance diversion, resulting in delayed treatment and transportation (Hoot & Aronsky, 2008; Olshaker & Rathlev, 2006). In addition, the EDs are further compounded by the lack of surge capacity for providing medical care in case of a sudden influx of patients during mass casualty events (e.g., mass shooting, civil riot; Braithwaite et al., 2017; Kaji et al., 2007). On the other hand, ED personnel, who have to deal with excessive treatment load under tight circumstances, suffer from stress, fatigue, and burnout (Healy & Tyrrell, 2011). Further threatened by the risk of litigation for medical malpractice, EDs face stubborn challenges of maintaining sufficient medical and nursing staff (Institute of Medicine, 2007). Therefore, it is apparent that sustained performance in such work environment with high levels of uncertainty requires "an ability of [the] system to adjust its functioning prior to, during, or following changes and disturbances"—a system property defined as resilience (Hollnagel, 2011, p. xxxvi).

Although there are many specialties suitable for resilience research in healthcare, EDs have been considered particularly well-suited to investigating resilience in action. Under complex and challenging circumstances, EDs have shown the ability to sustain acceptable levels of performance and thus served as a proper venue to study resilience (Righi et al., 2015). By acknowledging such opportunities, the Resilience Engineering (RE) approach views variability of performance as a

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necessary phenomenon to cope with complexity (Hollnagel, 2014; Hollnagel et al., 2006). As an example of the RE approach in EDs, Sujan et al. (2015) uncovered emergency medical technicians' 'secret' second handover to ED nurses, as opposed to the single handover protocol. The seemingly informal and redundant handover practice in EDs shows a level of performance adjustment that is essential to resolve conflicts between divergent goals such as clinical safety and handover efficiency. Similarly, Stephens (2010) observed the advent of a 'flex unit' for psychiatric patients, in response to colliding demands between reducing the ED load and providing required care. By creating a small, flexible unit and assigning specialized personnel on it, the EDs were able to maintain necessary physical space and medical staff. Such adjustments are often characterized as work-as-done (WAD), and comparisons have been drawn to work-as-imagined (WAI) to shed light on resilient performance (Hollnagel, 2016; Wreathall, 2006). The importance of such adjustment has been highlighted particularly for unexpected, rare events. For instance, Hunte (2017) attributed an ED's resilient response to a civil riot after a huge sporting event to proper adjustment of the system by anticipating future demands and putting more resource margins proactively for potential increase in a patient volume.

Although the attention to resilience in EDs has increased markedly over the last decade (Fairbanks et al., 2014), existing studies have predominantly relied upon case-based approaches. While case-study approaches to investigate resilience in EDs are well-documented, understanding generalizable patterns may provide further opportunities to address challenges in practice (Woods & Christoffersen, 2002). However, generalizable models and methods for resilience in EDs remain an overall research gap (Braithwaite et al., 2017; Patriarca et al., 2017). As part of a larger research effort to address this gap, this paper documents our findings from a systematic review of literature utilizing a three-pronged approach. First, this paper documents our attempt at providing generalizable adjustment patterns of resilient performance in EDs. Second, we identified five conceptual models of resilience, highlighting characteristic facets of resilience in EDs. Third, an inventory of strategies to enhance the resilient performance in EDs are presented in terms of four essential elements in EDs. Finally, the patterns and strategies are integrated into the resilience models and practical implications on the performance adjustment are discussed.

2. Method

As shown in Fig. 1, the search and inclusion of relevant articles for the current study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) framework (Moher et al., 2009). To capture emerging themes across the literature to be included and synthesize them, qualitative methods such as integrative synthesis, narrative summary and thematic analysis approaches (Dixon-Woods et al., 2005) were adopted.

2.1. Search strategy

Five search databases (MEDLINE, EMBASE, Compendex, Safety Science, and Google Scholar) were included in the search. Three sets of search terms were used: (1) 'resilience' or 'resilience engineering' (target construct), (2) 'emergency department' or 'emergency room' (target context), and (3) 'pattern' or 'model' or 'strategy' (target finding). These free-text search terms were logically combined using Boolean operators to yield the following search criteria: '(resilience OR "resilience engineering") AND ("emergency department" OR "emergency room" OR healthcare) AND (pattern OR model OR strategy)'. Since many articles regarding resilience and RE have been published in gray literature (Patriarca et al., 2017), Google Scholar was included in the literature search. However, since Google Scholar contains a variety of gray literature and is searched via full-text publications, exclusion terms far from the focus of the current review were applied to Google Scholar search: '-violence -children -depression -architecture'. As practiced in other review studies of Resilience Engineering (Patriarca et al., 2018; Pillay, 2017), chapters of RE books (Resilient Health Care Vol. 1, 2, and 3, Delivering Resilient Health Care, Resilience Engineering: Concepts and Precepts, Resilience Engineering in Practice Vol. 1 and 2, Resilience Engineering Perspectives Vol. 1 and 2) were searched manually in accordance with the search criteria.

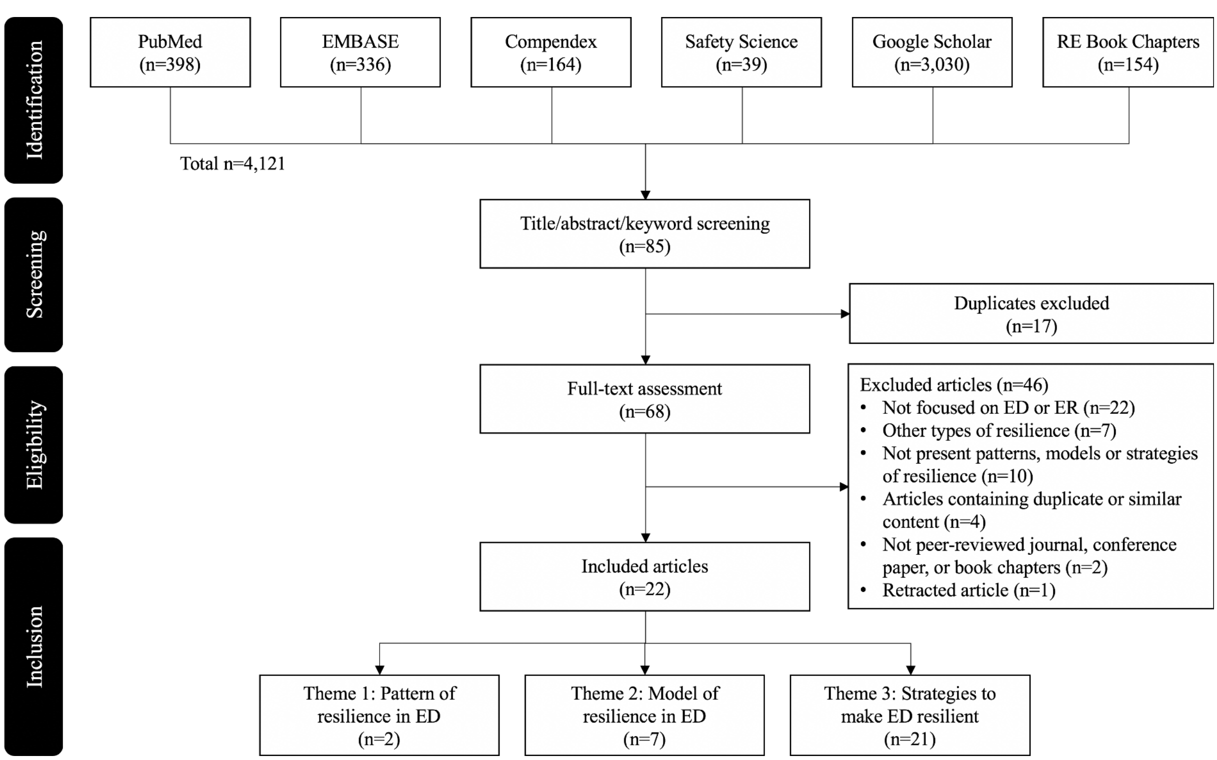

Fig. 1. The PRISMA diagram for the review process employed in this study.

2.2. Inclusion and exclusion criteria

After search results were obtained from each database using search terms, articles were screened based on the title, abstract, and keywords. Articles published in English and between 2005 and 2018 were included. Duplicates were removed among the chosen articles. Finally, full-text articles were retrieved and assessed for their eligibility. Articles were included if: (1) they described organizational resilience of hospital-based emergency care contexts (e.g., ED, ER); (2) they were a peer-reviewed journal publication, a conference paper, or a book chapter; and, (3) they were focused on either performance patterns, theoretical models, or practical strategies for resilience. Conversely, articles were excluded if: (1) they examined resilience of other types or domains (e.g., psychological, physiological, financial); (2) they are other types of documents (e.g., thesis, technical report, editorial, white paper); and, (3) they did not specifically present patterns, models, or strategies although resilience was an overarching concept of those articles. Articles having very similar content (a book chapter written based on a peer-review journal or conference paper) were also excluded.

To check the applicability of the inclusion criteria, the inter-coder agreement was assessed for the screening and full-text assessment with one of the co-authors. The agreement between two coders (CS and AR) was 82.4% for the screening and 90.5% for the full-text assessment.

3. Results

3.1. Search results

In total, 22 articles that met the inclusion criteria were included in the review. Table 1 shows a summary of the literature including the country in which the study was conducted, the method used, major findings, and themes identified from the article.

All of the studies included in the review were conducted in the Americas (USA, Canada, Brazil) and Europe (UK, Sweden, Israel). With the exception of four conceptual papers that made theoretical arguments, the remainder of the included articles were based on descriptive research conducted in associated methods such as ethnography, observation, interview, case study, and document analysis. Findings of the article were classified into three themes: pattern of resilient performance in EDs, models of resilience in EDs, and strategies to make EDs resilient.

3.2. Themes that emerged from the included literature

3.2.1. Patterns of performance adjustment in EDs

Four types of performance adjustment patterns in EDs were identified from literature (Table 2): *Adjustment by Matching, Extending, Sustaining, and Transforming* (Fairbanks et al., 2014; Nemeth et al., 2008). Each of the adjustment patterns is characterized by the way the ED changes its performance depending on the demand of adverse events. *Adjustment by Matching* occurs within normal operating capacity of an ED in such a way that the demands are met by deploying existing resources on a 'run-of-the-mill' basis (Nemeth et al., 2008). For instance, individuals injured in a single near-fatal car accident may be handled by using or adapting the existing ED resources. Once the demands exceed the normal operating capacity, the ED seeks and exploits additional resources to extend its response capacity (*Adjustment by Extending*). For a multi-vehicle crash involving multiple severe injuries or fatalities, the ED may require not only internal resources but also external resources to match the demand required in this scenario. When the demands persist for a prolonged period, the ED begins to lose control over the situation and gravitates towards the persistent demands with less sense of what is occurring in the ED, a phenomenon called 'free fall' (Fairbanks et al., 2014; Wears et al., 2006). In this state, the ED attempts to continue to restore control as time lapses and the demands diminish (*Adjustment by Sustaining*). In case of an extreme emergency, the ED is required to reorganize and reconfigure its functions to a greater extent (e.g., the entire hospital functions as an ED during a mass casualty incident) (*Adjustment by Transforming*).

It is to be noted that the patterns of resilient performance in an ED's response to adverse events are derived from some representative contexts and thus they may not be sufficient to explain the transitions or relationships between different adjustment regimens. To facilitate the understanding of such patterns to be more generalizable, five conceptual models of resilience are presented in the following subsection.

3.2.2. Models of ED resilience

Conceptual models or simplified representations facilitate understanding of abstract systems constructs such as resilience and may lead to a common knowledge base that can be useful for improving work practices or developing new tools (Woods & Sarter, 1993). From the current review, five conceptual models of resilience applicable to EDs were identified: State-Space, Stress-Strain Curve, Temporal Dynamic, Stretched Systems, and Variety-Space (Table 3).

(1) State-Space Model

The State-Space model (Hollnagel & Sundström, 2006) assumes that a system functions upon a set of discrete states that are interconnected. Resilience in this model is described as the ability to make a transition between different operational states so that the system can return to its normal state. The State-Space model consists of five adjacent functioning states: normal, regular reduced, irregular reduced, disturbed, and suspended functioning (or 'repair') states (Wears et al., 2008, 2006). In this model, an ED is assumed to begin from a normal state. When there is a gradual or chronic increase in demand, the ED moves to a regular reduced functioning state with lowered buffering capacity. A sudden and rapid surge shifts the ED into an irregular reduced functioning state. The reduced functioning states (e.g., regular or irregular) remain under the 'horizon of tractability' as the system is able to keep situations under control and return to the normal state (Wears et al., 2008). Over this horizon, the function of the ED gets disturbed by additional yet uncompensated patient load and even the ED may halt its routine operations to regain control (Wears et al., 2006), each representing 'disturbed functioning state' and 'suspended functioning state'.

(2) Stress-Strain Curve Model.

The Stress-Strain model uses the analogy of physical properties of materials (e.g., elasticity) to describe a relationship between work demand and system performance. As an external force is applied to the material, it uniformly stretches to a yield point representing an elastic region. Beyond this point, the material does not stretch linearly and does not return to its original point, resulting in some deformation or rupture. Analogous to the physical property of a material, resilience of a system is viewed as its capability to stretch to changing work demand (Woods & Wreathall, 2008). As long as the demand occurs under planned capacity, an ED can stretch to accommodate the demand in a linear fashion. Once the demand exceeds the capacity, the ED may not be able to stretch in proportion to the increased demand. If such excess demand is not compensated, the ED may experience failure (similar to the fracture point of a material) or reconfigure and reorganize itself to operate in a new mode (Allen et al., 2016; Woods & Wreathall, 2008). Nonetheless, the newly created capacity earned from the reconfiguration may come at a greater cost from a hospital systems' perspective as it would require additional resources to be spent in unconventional ways (Wears et al., 2008).

Table 1
Descriptive summary of the articles included in the review.

Authors (year)	Country	Method	Major findings	Theme 1	Theme 2	Theme 3
[1]Allen et al. (2016)		Conceptual paper	System resilience (e.g., safe operating envelope, stress–strain) models were collocated and compared.		✓	
[2]Anders et al. (2006)	USA	Observation, case study	Observations from an ED were explained in terms of properties of resilience (e.g., buffering capacity, cross-scale interaction).			✓
[3]Back et al. (2017)	UK	Ethnography, document analysis	Some of the ED escalation policies (‘work-as-imagined’) were not implemented due to the situational limitations and thus adapted to meet changing demands (‘work-as-done’)			✓
[4]Braithwaite et al. (2017)	Australia, UK, Canada	Case study	ED practices were analyzed to reveal insights on resilience from blunt and sharp ends of an organization in terms of patient flow and shift handover.			✓
[5]Cook and Nemeth (2006)	Israel	Case study	A response to a bus bombing was described in which emergency care function was shifted drastically to meet sudden excess needs.			✓
[6]Fairbanks et al. (2014)		Conceptual paper	Representative ED practices and theories of resilience engineering were integrated to provide an overview of resilience research in health care.	✓		✓
[7]Fairbanks et al. (2013)	USA	Case study	Two contrasting cases, resilient failure and brittle success, were introduced to claim that resilience and success should be treated differently.			✓
[8]Hunte (2017)	Canada	Case study	A local ED’s resilient performance during the treatment of patients caused by a riot after a major sport game was examined.			✓
[9]Miller and Xiao (2007)	USA	Interview	Demand compensation strategies were identified at three organizational levels (director, scheduler, and charging nurse)		✓	✓
[10]Nemeth et al. (2011)	USA	Observation, interview	Using multiple, qualitative Human Factors methods, how ED clinicians handle variable and complex demands throughout the patient flow was examined.			✓
[11]Nemeth et al. (2008)	USA	Observation	ED workers’ adaptive strategies were identified from a response to surge in patient numbers and an improved design of an infusion pump display was presented.	✓	✓	✓
[12]Perry et al. (2008)	USA	Case study	An ED medication system adapted for short-term care caused confliction with another medication system designed for long-term care in case of ED overcrowding.			✓
[13]Rankin et al. (2014)	Sweden	Focus group	Interactions between blunt and sharp ends’ adaptive strategies of emergency care settings were described using a variety space diagram.		✓	
[14]Stephens et al. (2015)	USA	Observation	A case of patient boarding was studied as a strategy practiced in EDs to regulate the capacity for adaptations.			✓
[15]Stephens et al. (2011)	USA	Observation	Three strategies (defensive, autonomous, and cooperative) for resilient EDs were identified.			✓
[16]Sujan et al. (2015)	UK	Observation, interview	‘Secret second handover’ was revealed as an example of dynamic trade-off to handle tension in emergency care boundaries.			✓
[17]Therrien et al. (2017)		Conceptual paper	Resilience factors are identified in four S’s of surge capacity (staff, stuff, structure, and systems).			✓
[18]Wachs and Saurin (2018)	Brazil	Observation, interview, document analysis	Work constraints and resilience skills to deal with the constraints were identified from ED practitioners in relation to the use of procedures.			✓
[19]Wachs et al. (2016)	Brazil, USA	Case study, interview	Work constraints and resilience skills to address the constraints were identified from EDs of two countries.			✓
[20]Wears et al. (2006)	USA	Case study	ED’s resilience performance in two critical incidents in EDs were introduced and then described in a state-space model.		✓	✓
[21]Wears et al. (2008)	USA	Interview, document analysis	Two cases from overcrowded EDs were introduced and three resilience models were used to illustrate the ED’s performance.		✓	✓
[22]Woods and Wreathall (2008)		Conceptual paper	A stress–strain model was theorized to explain resilience and brittleness of a complex system including health care.		✓	

Table 2
Four patterns of resilience in EDs.

Emerged pattern	Fairbanks et al. (2014)			Nemeth et al. (2008)		
	Event scale	Case description	ED performance	Case description	ED performance	Recovery
Adjustment by Matching	Very small	Soft emergency surgery	Coordinating competing demands for resources	Usual ED situations or 'run-of-the-mill'	Adapt existing resources	Rapid
Adjustment by Extending	Small	Automated medication system failure	Designate informal workforce for pharmacy dispense	Increased demand	Identify and reorganize additional resources	Delayed
Adjustment by Sustaining	Medium	Overwhelming volume of patient or 'free fall'	Forgo routine tasks, continue operations without central guidance	Demand that requires departmental change	Abandon other cares except life-threatening illness	Sustained
Adjustment by Transforming	Large	Suicide bus bombing	Reorganize the entire facility	Catastrophic event	Completely reorganize work	Sustained

(3) Temporal Dynamic Model.

While the State-Space model and Stress-Strain Curve model are based on the relationship between demand and performance of an ED, the Temporal Dynamic model represents how an ED's actual performance adjustment amplitude increases or decreases in response to varying demands along a temporal dimension (Wears et al., 2006). The Temporal Dynamic model compares the magnitude of demand and response of the ED to the demand in a chronological manner. Therefore, the temporal changes in demand, response, and the relationship between the two are traceable in this model. For instance, the elastic performance of the ED, which was conceived in the Stress-Strain Curve model, can be represented with equivalence between the demand and response. Likewise, uncompensated demand means the difference between the magnitudes of demand on ED and corresponding response performance. In the Temporal Dynamic model, the time lag between the demand and response, or 'hysteresis', can also be captured (Wears et al., 2006).

(4) Stretched Systems Model.

This model is derived from the Law of Stretched Systems (Hirschhorn, 1997). The Law denotes that every socio-technical system tends to stretch its capacity to the full extent when there is an opportunity to exploit such capacity. Grounded in this Law, the Stretched Systems model explains a phenomenon that a system's operating boundary flexibly expands or shrinks through dynamic interplay among three driving forces: economic pressure, workload release, and efforts for safety (Cook & Rasmussen, 2005). Thus, the model is also called 'safety operating envelope' (Allen et al., 2016). According to the Law of Stretched Systems, the hospital's upper management, motivated towards efficiency and profitability, pushes the operating boundary by exploiting increased capabilities (e.g., technical innovations, new work protocols). At the same time, front-end employees in EDs (e.g., physicians and nurses) relieve workload burdened on them by exerting less rigor. Consequently, these two forces in combination drive the ED's operating point towards an unacceptable boundary over which the breakdown of the system (e.g., incident) is likely (Woods & Hollnagel, 2006). Hence, resilience in this model means that the operating point of the ED is kept within the safe operating boundary. To be resilient, the model emphasizes the ED personnel's awareness and calibration of how close the current operating point is to the ED's unacceptable boundary (Allen et al., 2016; Nemeth et al., 2008). With respect to the driving forces in EDs, Miller and Xiao (2007) identified several affecting factors such as number of admissions, type and amount of medical procedures employed, shift and holiday schedule, overtime, and the sharing of limited medical equipment.

(5) Variety-Space Model.

The Variety-Space model is a multi-dimensional model that aims at describing different 'varieties' or distinguishable states of a system in which sharp ends (i.e., those actually operating EDs at the point of care) and blunt ends (i.e., those managing policies and procedures) of the system can function (Rankin et al., 2014). Grounded in the Law of Requisite Variety (Ashby, 1991), this model highlights relationships among the variety of sensemaking (SV), the variety of control (CV) and the variety of disturbance (DV). Three possible states for SV and CV are *basic*, *shifted*, and *extended* and three types of disturbance are *regular*, *irregular*, and *exceptional* (Rankin et al., 2014). Resilience in this model is viewed as the system's capability of matching SV and CV with DV to handle disturbances (Hollnagel & Woods, 2005). Based on this concept, a resilient ED is able to make sense of disruptions in itself and to mobilize control measures to mitigate the disruptions. The Variety-Space model describes such process with two dimensions of the ED, the sharp and blunt ends. On one hand, locally available strategies are improvised

Table 3
Five models of resilience in EDs.

Model	Allen et al. (2016)	Miller and Xiao (2007)	Nemeth et al. (2008)	Rankin et al. (2014)	Wears et al. (2006)	Wears et al. (2008)	Woods and Wreathall (2008)
State-space					✓	✓	
Stress-strain curve	✓					✓	✓
Temporal dynamic						✓	
Stretched systems	✓	✓	✓				
Variety-space				✓			

and implemented at the sharp end during the course of coping with varying disturbances in EDs. For example, a study found out that doctors in an ED made a decision to send fathers of newborn babies home to increase the number of available beds where there was no protocol (Rankin et al., 2014). On the other hand, global changes such as adopting a new hygiene protocol are created and operationalized by the blunt end, and then pushed to the sharp end. A failure in EDs can arise when the SV and CV that the ED can rely on fall short of the DV.

3.2.3. Strategies to make EDs resilient

This review found that 19 out of 22 articles addressed resilience strategies, either anecdotally or comprehensively identified from ED operations. These strategies are then classified into four important elements of EDs: *staff, supplies, space,* and *sequence* (four S's taxonomy) (Therrien et al., 2017). Table 4 presents a matrix in which these elements are matched with the four patterns of performance adjustment in EDs. Since *Adjustment by Sustaining* can be considered as a prolonged form of *Adjustment by Extending* and both require additional capabilities to be recruited, the two are grouped together in this summary.

First, strategies for *Adjustment by Matching* aim to protect an ED from excess demands and manage its planned capacity. For example, EDs often increase the number of attending physicians and nurses for usually busy hours in an preemptive manner (Back et al., 2017; Hunte, 2017). On the contrary, an ED may restrict the influx of emergency patients by diverting an ambulance to other EDs (Wachs et al., 2016). Alternatively, the ED may discharge stable patients earlier than it normally does (Stephens et al., 2011). 'Bed-hiding' is another example that the ED employs to protect itself from potential future workload (Stephens et al., 2015). Such defensive strategies may be helpful in protecting an ED's capacity; nonetheless, it comes at the cost of exploiting the margin of another ED (due to ambulance diversion and bed-hiding), and increased risks of readmission (for early discharged patients). For medical supplies, ED personnel can stockpile or hoard commonly required medicines and consumable materials (Fairbanks et al., 2014) or prepare necessary supplies and equipment for the following shift to restore a buffering capacity (Miller & Xiao, 2007).

Second, *Adjustment by Extending* and *Adjustment by Sustaining* in the EDs are enabled by strategies that obtain additional capacity from local and adjacent sources. A common practice to manage personnel capacity is done through extending work shifts or taking double shifts (Nemeth et al., 2008). An additional staffing capacity is also generated through cooperation between neighboring units. For example, an ED can share a common pool of physicians and nurses with adjacent units such as Intensive Care Unit (ICU) or Operating Room (OR). For ED patients that require particular needs (e.g., psychiatric patients), the ED may temporarily create a sub-unit or a 'flex unit' that specialized personnel can oversee (Stephens et al., 2015). Similarly, full-time staff is dedicated to transporting patients between the ED and other units (Wachs et al., 2016). Given the limited stock of medicines and medical equipment, a marginal capacity for supplies can be made by substituting with other compatible items or switching to an equivalent medication system (Perry et al., 2008), and reallocating already deployed items to more critical cases (Nemeth et al., 2008). To recruit additional spatial capacity, the ED can leverage intra- and inter-departmental strategies. The intra-departmental strategies are concerned with creating extra spaces (e.g., stretchers, beds, chairs, and hallways) within the ED while the inter-departmental strategies aim to share spaces with functionally compatible units (Wears et al., 2006) or setting up external clinics for temporary and special needs (e.g., pandemic flu) (Therrien et al., 2017). Similar to the reallocation of supplies, the ED can generate additional capacity by reordering or replanning medical procedures considering the urgency of a patient's condition. For example, cardiovascular or abdominal surgery can be conducted before less urgent orthopedic or plastic surgery (Wachs & Saurin, 2018; Wachs et al., 2016).

Third, strategies for *Adjustment by Transforming* are likely to be seen in extreme events. To cope with unconventional demand on EDs, additional capabilities are sometimes earned by sacrificing other goals, functions, or tasks. One example of the sacrifice is a trans-hospital strategy that converts non-ED facilities into a temporary space that provides emergency care during mass casualty events (Braithwaite et al., 2017). Similar strategies are available for staff and supplies. For instance, non-ED personnel or off-duty workforce were mobilized with other functions being abandoned or degraded (Back et al., 2017), and an ambulatory (portable) flutter valve was used for a patient with traumatic pneumothorax (Hunte, 2017). Such sacrificing behaviors may be practiced in the sequence of the ED care process. In extreme cases (e.g., severe head injury), non-essential tasks (e.g., routine paperwork) may be bypassed and direct emergency care can be given in a triage area (Cook & Nemeth, 2006; Fairbanks et al., 2014). A more radical example of the sacrifice judgment is prioritizing a patient with a life-threatening condition over another with less severe symptoms (Wachs et al., 2016). However, the newly created capacity via transformative adjustment comes at the expense of forgoing or compromising other units' capabilities.

4. Discussion

4.1. Integrating patterns and strategies into models of resilience in ED

Although each theme presented in this paper provides meaningful insights on its own right, the integration of such findings may provide more comprehensive understanding of resilience in ED. In such regards, the patterns and some representative strategies of performance adjustment are incorporated into the respective model of resilience in ED in the following subsections.

(1) ED resilience in State-Space model

Fig. 2 illustrates four patterns of resilience in EDs in the State-Space model. In EDs, handling scheduled or predicted demands by utilizing existing resources can be seen as regular reduced functioning with buffering capacity consumed (*Adjustment by Matching*). If the demands persist or surge in an abnormal manner, the ED moves to an irregular reduced functioning state in which additional resources need to be recruited by borrowing or sharing clinicians or by making up additional spaces (*Adjustment by Extending*). When such demands remain uncompensated and finally exceed the margin of safety or 'horizon of tractability' to which the ED can adequately function, it drifts into a disturbed functioning state (Wears et al., 2006). It is desirable for the ED to recover from the disturbed functioning state by maintaining

Table 4
Strategies to enhance resilience capacity in EDs.

Pattern	Staff	Supplies	Space	Sequence
Adjustment by Matching	● **Increasing** the number of designated ED personnel as a defensive strategy[3,19]	● **Stockpiling** or hoarding essential medical items[6,14,16,19] ● **Preparing** equipment and supplies for the following shift[9]	● **Intra-departmental** strategy: 'bed-hiding' when to reserve spatial capacity for potential large needs and relocating patients to a less busy area[3,14,15]	● **Restricting** the patient flow from a preceding process (e.g., diverting an ambulance, sending a non-urgent patient to another service)[3,15,20] ● **Expediting** or 'selling' against 'gatekeeping' the patient flow via discharging to another department or displacing more stable patients earlier than it normally does[3,4,14,16]
Adjustment by extending/ adjustment by sustaining	● **Borrowing** strategy: extending work shift, working double shift, or borrowing staff outside ED as an assistant[8,15,19] ● **Autonomous** strategy: creating a temporal sub-unit or a 'flex unit' within the ED that handles special cases[3,14,15] ● **Cooperative** strategy: sharing a common pool between adjacent units[9,14,15]	● **Substituting** among equivalent medicine or switching to equivalent medication system[6,12] ● **Reallocating** for more critical needs[11]	● **Intra-departmental** strategy: setting up additional stretchers, beds, chairs for temporary patient boarding[2,10,11,18,20,21] ● **Inter-departmental** strategy: sharing spaces between functional compatible units (e.g., ICU, OR) or establishing external clinics for special temporary needs[15,17,21]	● **Reordering** or replanning medical procedures based on the urgency of a patient (e.g., cardio-vascular surgery before orthopedic or plastic surgery)[10,18,19] ● **Repeating** clinical and organizational practices to increase safety (e.g., second handover)[4,16]
Adjustment by Transforming	● **Absorptive** strategy: mobilizing non-ED or off-duty workforce by sacrificing other functions[3,6,8]	● **Adapting** for unconventional usage (i.e., altering the original usage for a different need)[8]	● **Trans-hospital** strategy: converting out-of-ED premises to provide emergency care[4,8,20,21]	● **Skipping** non-critical tasks (e.g., paperwork, charting), or giving direct care in triage area[4–6] ● **Prioritizing** more critical patients before those with less severe injury[4,7,18,19,21]

Note: Superscripts indicate articles numbers (see Table 1) from which the strategies were identified.

strategies already in use (*Adjustment by Sustaining*); however, the ED may retreat and get suspended temporarily if it fails to recover. Resuming the ED's normal function out of the suspension then requires the ED performance to be radically changed (*Adjustment by Transforming*). For example, the ED provides direct care in a triage area, assigns non-standard roles to staff, or skips non-critical processes (Fairbanks et al., 2014). While the State-Space model represents distinct ED states and transitions, it is limited in terms of representing the temporal nature of transitions. It also does not capture cross-scale interaction between sharp and blunt ends involved in the transitions.

(2) ED resilience in Stress-Strain Curve model

Fig. 3 depicts the four patterns of ED resilience on Stress-Strain Curve model. In the context of EDs, an influx of patients acts as stress and corresponding caregiving performance is considered as strain. A first-order resilient performance moves on a straight line on which the ED can utilize planned-for buffering capacity to absorb the stress (*Adjustment by Matching*) and restore the consumed capacity. A defensive strategy such as assigning more physicians and nurses for busy days or hours can be a way to increase such planned-for capacity. However, as the stress resulting from an emergency event exceeds the designed capacity, the ED slips into the 'extra-region' that indicates safety margin and tolerance for excessive demands. The ED in the extra-region necessitates additional resources and strategies either for a relatively shorter period of time (*Adjustment by Extending*), or for a longer period (*Adjustment by Sustaining*). These second-order adaptations may take place by exploiting extra resources locally (e.g., physicians and beds from other units). If the ED faces excessive demands which are not effectively compensated, then the ED needs to reconfigure itself into a new mode of operation. This transformation is referred to as an 'adaptive stretch' that brings in a new stress-strain curve (*Adjustment by Transforming*) (Woods & Wreathall, 2008). When the adaptive stretch is no longer possible, the ED becomes brittle and at some point, reaches a failure point. To prevent a sudden or brittle failure of the ED, the system requires 'graceful extension' during which the ED slowly absorbs the stress and gradually degrades until the final breakdown (Woods, 2015). The Stress-Strain Curve model illustrates continuous adjustment of the ED performance over time; however, this model represents only the overall response to demands and provides no details about cross-scale interaction between the system elements.

(3) ED resilience in Temporal Dynamic model

Fig. 4 shows dynamic interactions between demands on an ED and corresponding response incorporating four patterns of performance adjustment on a temporal horizon. When the demands are less than the ED's buffer capacity, emerging demands are offset by matching the ED performance ($D = P$, *Adjustment by Matching*). As the demands increase and consume the existing resources, the ED recruits additional resources from local sources ($D > P$, *Adjustment by Extending*) and such a condition may linger, requiring all the available resources to be recruited ($D > P$, *Adjustment by Sustaining*). Similar to the extra-region in the Stress-Strain Curve model (see Fig. 3), these two phases, where $D > P$, represent the margin and tolerance of safety with which the ED can still function without drifting into failure. In cases where the demands are unexpectedly high and thus cannot be met by the already recruited resources, the ED needs to be reconfigured to create new operational capacity ($D \gg P$, *Adjustment by Transforming*). This is especially true in a scenario where a hospital that deals with mass casualty incidents (e.g., a terrorist attack) and faces severe emergency care needs, transforms itself into a huge ED by sacrificing other functions (Nemeth et al., 2008). Similar to the Stress-Strain Curve, the Temporal Dynamic model is limited in describing how the front-line workers at the sharp end and the upper-level management of the hospital interact to adjust the ED performance.

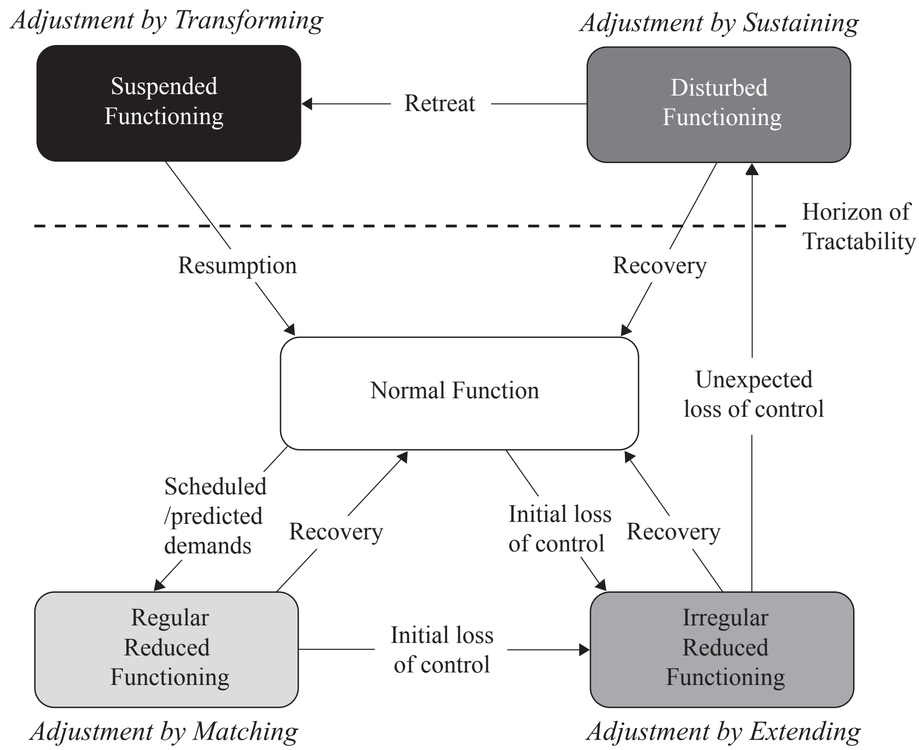

Fig. 2. State-space model for ED resilience (adapted from Hollnagel and Sundström (2006) and Wears et al. (2008)).

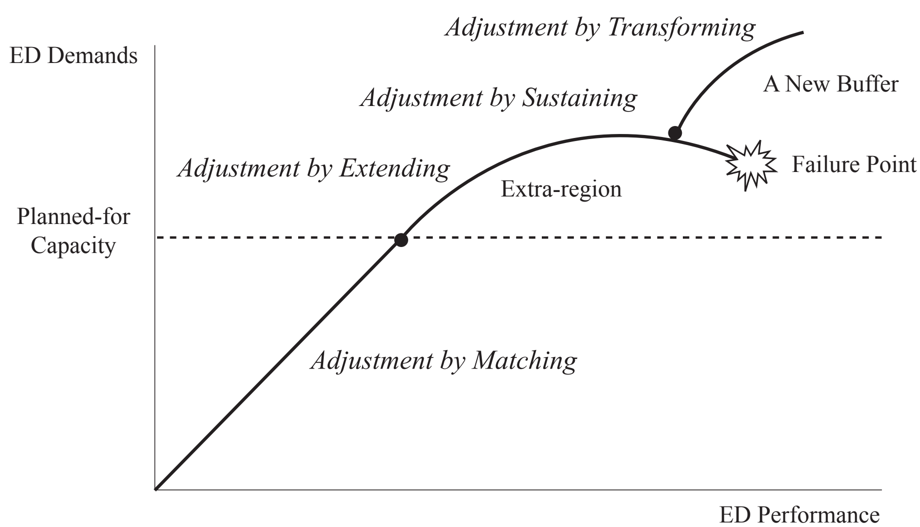

Fig. 3. Stress-strain curve model for ED resilience (adapted from Woods and Wreathall (2008)).

(4) ED resilience in Stretched Systems model

Fig. 5 depicts how the ED's four resilient performance patterns can occur near its operating boundary. First, the ED's performance capacity can stretch as it consumes its buffering capacity (e.g., staff, supplies and spaces) until the marginal operating boundary (*Adjustment by Matching*). As the ED is pushed over the marginal operating boundary, two resilient behaviors can occur in the ED: the ED recovers from slightly reduced safety margin (*Adjustment by Extending*), or the ED returns from largely consumed safety margin (*Adjustment by Sustaining*). Sharing clinical staff and utilizing non-designated spaces (e.g., hallways) can help increase such margin. In another case, a paramedic's secondary handover to ED nurses (Sujan et al., 2015) may be regarded as a safety effort to ensure an adequate margin against the efficiency-oriented single handover protocol. Once the ED's operating point passes beyond the unacceptable operating boundary, the ED must bounce back into acceptable boundary or the ED may find a new marginal boundary by transforming its functioning (*Adjustment by Transforming*).

(5) ED resilience in Variety-Space model

Fig. 6 represents how an ED's resilient performance can occur in the Variety-Space with respect to making sense of and controlling the emergency events. For a regular or routine event, both ends possess *basic* or pre-planned strategies for sensemaking and control (*Adjustment by Matching*). As the demands from emergency events escalate to a higher level (e.g., continual influx of ED patients), the SV and CV are transitioned to the *shifted* state in which locally available strategies (e.g., 'bed-hiding', 'patient-selling') are present, although the blunt end of the ED may not have established (does not accept) such strategies a

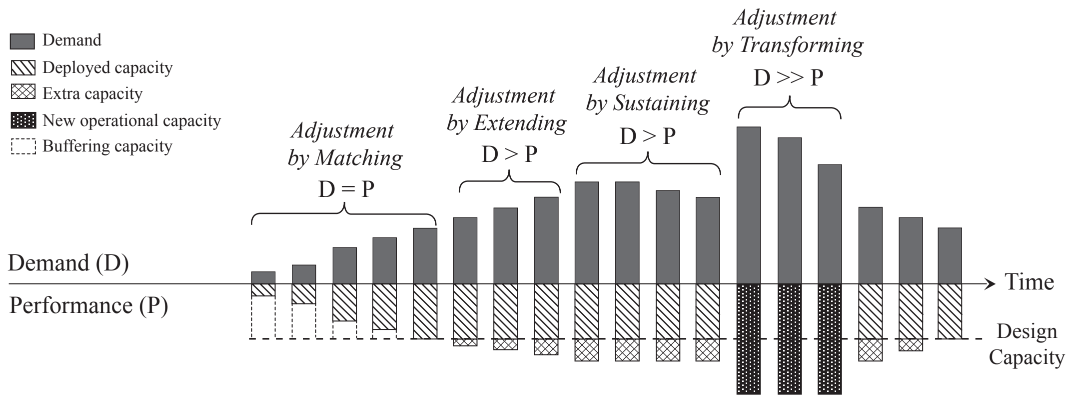

Fig. 4. Temporal dynamic model (adapted from Wears et al. (2006)).

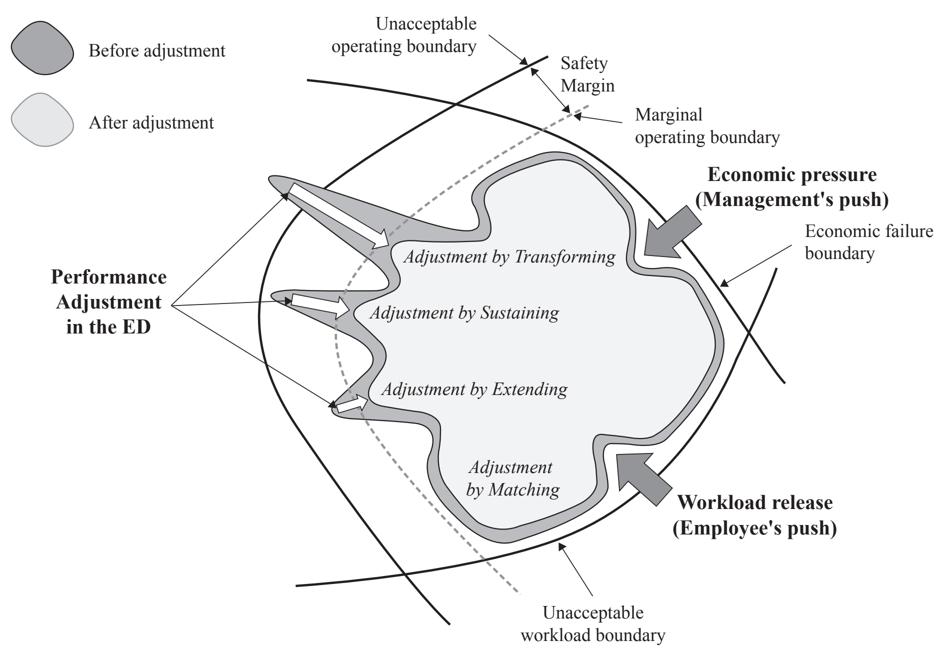

Fig. 5. Stretched systems model for ED resilience (adapted from Miller and Xiao (2007)).

priori (*Adjustment by Extending*). Likewise, when the ED encounters irregularly high or persistent demands, the sharp end workforce runs into shifted SV and CV and seeks to sustain its control over the situation by locally adapting or improvising (e.g., creation of a 'flex unit') and the reordering of surgical procedures (*Adjustment by Sustaining*). For an extreme event that imposes exceptional demands to the ED such as mass casualty incident where neither end has available strategies a priori, *extended* or *transformative* strategies (*Adjustment by Transforming*) for sensemaking and control such as providing direct at a triage area or skipping paperwork are necessary at both ends. Otherwise, the ED may lose its control over the disruptive events and drift into a failure. While the Variety-Space model delineates the interaction between the sharp and blunt ends of the ED involved in adjusting ED performance, the model does not represent a temporal aspect and the continuum of performance adjustment as shown in Stress-Strain Curve model.

4.2. Strengths, weaknesses, and recommended usage for ED resilience models

By incorporating findings from hospital-based emergency care studies, this paper has summarized and synthesized the emerging patterns of performance adjustment in the EDs. The patterns of resilience in the EDs, namely, *Adjustment by Matching*, *Extending*, *Sustaining*, and *Transforming*, indicate a set of available operating modes that enable a system under a complex and uncertain environment to address demands and avoid critical failures. Based on the Safety-II perspective that focuses on a system's ability to adjust, future efforts should seek to dampen or reinforce the variability in the EDs, not to eliminate it through a 'find and fix' approach (Hollnagel, 2017; Sujan et al., 2017). In other words, variable behaviors of ED personnel that lead to success in everyday operations need to be supported while those that lead to failure or undesired outcomes need to be tempered. Such variabilities are often captured through understanding the difference between WAI and WAD by investigating performance adjustment or workarounds observed in everyday clinical work (Hollnagel, 2016). Indeed, the present review indicates the majority of previous RE research in EDs has focused on case-based approaches to understand such performance adjustments. The reconciliation between the WAI and WAD can be sought by incorporating the performance adjustment patterns and strategies into the design of ED aspects such as facilities, tools, or work protocols.

Designing or engineering resilience into the EDs, however, needs a frame of reference that abstracts complex phenomena found in the field of practice into generalizable knowledge. In light of such need, this

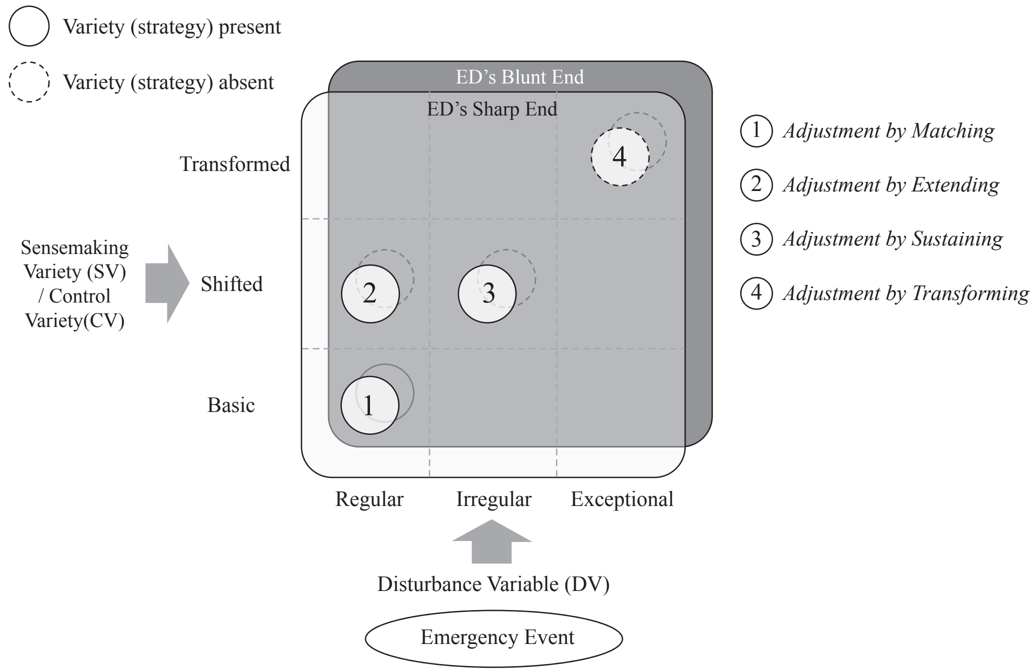

Fig. 6. Variety-space model for ED Resilience (adapted from Rankin et al. (2014)).

paper has provided five conceptual models of ED resilience that aid in illustrating the common patterns of performance adjustment: *State-Space* model, *Stress-Strain Curve* model, *Temporal Dynamic* model, *Stretched Systems* model, and *Variety-Space* model. Note that each model has strengths and weaknesses so the usage of a model may vary depending on properties of different EDs, type of interventions, and subject of inquiries (Table 5). For example, *State-Space* model depicts separate operating modes of the EDs and explains the transition among them. Hence, individual cases of performance adjustment are easily integrated into this model. If cross-scale interaction between sharp and blunt ends of a system needs to be taken into account, the *Variety-Space* model appears to be the most suitable among other models due to its ability to indicate different strategic modes and transition between them for different system elements. The *Stress-Strain Curve* model best represents the continuum of performance adjustment that occurs between demands on and capacity of the ED. Furthermore, the *Stress-Strain Curve* model is able to explain how a new buffer is created, and thus how the ED avoids drifting into a failure. The dynamic matching between the demand and corresponding performance on a dimension of time is well represented by the *Temporal Dynamic* model. While the temporal adjustment in EDs is properly described in the *Temporal Dynamic* model or possibly *Stress-Strain Curve* model, the spatial illustration of multiple performance adjustment patterns at the system boundaries is best captured in the *Stretched Systems* model.

The combination of the identified models may also facilitate the development of measures of resilience. There has been a persistent need to measure resilience owing to the dominant use of interpretative studies in the field of RE (Mendonca, 2016; Righi et al., 2015). Among the five resilience models, the *Stress-Strain Curve* model and the *Temporal Dynamic* model are the most promising to formulate measures of resilience in EDs (Wears et al., 2008). On one hand, two primary dimensions (i.e., demands and performance) presented in the models are quantifiable in the context of the EDs. The number or the rate of patients admitted to the EDs can be used as a reliable metric for the demands. In addition, the severity level of the patient (e.g., triage decision) and the type of needed medical procedures can further refine the metric of the demands (Hogan et al., 1999). On the other hand, common capacity measures employed in a hospital are potential candidates for quantifying ED performance. Such capacity measures include the number of inpatient beds, the number of caregivers (e.g., emergency physicians, nurses), the availability of adjacent units (e.g., OR, ICU) and major diagnostic devices such as medical imaging equipment (Green, 2005).

Table 5
Strength, weakness, and recommended usage for resilience models.

Resilience model	Strength	Weakness	Recommended usage
State-space	• Identifies distinct operating states • Describes inter-state transitions	• Does not provide the continuum of performance adjustment. • Does not explain interactions between different system levels	• To integrate individual cases of resilience observed from field practices
Variety-space	• Expands State-Space to the sharp end and the blunt end of the ED	• Does not provides the continuum of performance adjustment	• To find out in what situations either end requires to develop strategies to cope with disturbances
Stress-strain curve	• Explains linear and non-linear performance adjustment and creation of a new buffer capacity	• Does not describes how cross-scale interaction affects the performance adjustment	• To quantify overall demands and ED performance and find relationships between the two
Temporal dynamic	• Describes dynamic matching between demands and performance level	• Does not describes how cross-scale interaction affects the performance adjustment	• To depict temporal trends in demands and ED performance and monitor when demands exceed capacity
Stretched systems	• Illustrates multiple performance adjustment patterns that may occur at different parts of a system	• Does not explains temporal changes	• To represent the effects of system's driving forces on multiple parts of the system

Nevertheless, it is worth noting that resilience in EDs may be too tacit to measure as indicated by the prevalent qualitative studies. As one way to develop metrics, especially for ED performance, that are sensitive to capture resilient performance, the differentiation between adaptivity (e.g., a predetermined capacity) and resilience (e.g., performance beyond the design envelope) is suggested, the former concerning the availability of the resources and work procedures in EDs and the latter regarding the effectiveness of ED performance in actually utilizing such resources and procedures (Hoffman & Hancock, 2016).

This paper has offered a toolkit of strategies for resilience based on manipulation of 'four S's' of the ED system: *staff*, *supplies*, *space*, and *sequence*. These strategies indicate the adaptive capability of human practitioners in coping with complex and uncertain demands on EDs. That is, the variability of ED functions is not only inevitable but also necessary to maintain its daily operations. Therefore, the variability of performance in EDs needs to be dampened, not eliminated, so the EDs function within the acceptable boundary. The strategies presented in this paper may provide potential benefits in the face of excess demands in EDs; however, it must be noted that such strategies may have worked under unique circumstances. Thus, their applications to a wide range of scenarios may be limited and the implementation of the strategies requires much caution. The strategies mentioned here may be regarded as alternative options that help cultivate resilience skills (Safety-II) rather than clinical protocols that act as normative behavioral rules (Safety-I) (Sujan et al., 2017; Wachs & Saurin, 2018). By possessing monitoring capabilities that may be enabled by the said resilience measures, ED practitioners may be better equipped to anticipate future states and thus take proactive actions to maintain ED resilience.

The synthesis of frameworks for ED resilience provided in this paper may serve as the initial step in investigating practical improvement towards resilient EDs. Hence, future research is necessary to further validate the patterns, models, and strategies to help healthcare clinicians cope with everyday complex work in EDs. While EDs have been well suited to study resilience, the validity of evidences synthesized in this paper and applicability to other complex sociotechnical systems needs further investigation. In addition, this paper highlighted needs for quantifying resilience in the context of EDs. Future efforts may include designing practical methods that facilitate operationalization and quantitative analysis of resilience in EDs.

Including EDs, the needs for resilience are prevalent during everyday clinical work in healthcare (Hollnagel et al., 2013). In this regard, findings presented in this paper would serve as a reference of framework for understanding challenges experienced by other sectors of a hospital system and capturing unique ways to work around the difficulties. Such efforts would increase the applicability and utility of the performance adjustment patterns, conceptual models, and practical strategies for more resilient healthcare.

4.3. Risk of biases

Although a rigorous assessment of risk of bias was limited in that all of the included articles were based on qualitative research, biases that may exists in the articles should be acknowledged (Higgins & Green, 2008). First, a majority of included studies adopted descriptive methods such as observation, interview, and case study. Therefore, the findings reported in the articles are subject to authors' level of domain knowledge and its subjective application to an observed phenomenon. Second, there may be a publication bias since the current review did not consider all types of gray literature including internal documents and presentations, though conference papers were included. Third, it should be acknowledged that the included studies were conducted in the countries located in Europe and the Americas. Hence, findings from the included studies should be interpreted with caution for different countries that may have disparate ED policies and settings. Finally, there might be a duplication bias. Although four articles that contain duplicate or similar contents with others were removed during the full-text assessment, meaningful results of the studies may have been cross-referenced among literature.

4.4. Limitations of the current study

In addition to the risk incurred by the biases, several limitations of the current review need to be mentioned. First, the current review is limited to hospital-based emergency care settings such as EDs. Hence, applications of patterns, models, and strategies identified in this review to other critical healthcare contexts (e.g., ICUs) may be limited although such efforts are highly recommended. Second, it should be acknowledged that analysis methods for resilience were not the scope of the current review. For example, methods designed to examine resilience as an emergent phenomenon such as Functional Resonance Analysis Method (FRAM; Hollnagel, 2017) were not considered in this paper. Third, an assessment of the quality of evidence (e.g., effects of an intervention) was not conducted in the current review since descriptive research was predominant among literature regarding ED resilience. Thus, a focal point of a future literature review may be aimed at evaluating the degree of empirical evidence (Kitchenham & Charters, 2007) after additional evidences for resilient emergency care have been accumulated

5. Conclusion

Modern EDs are still preoccupied with traditional 'find-and-fix' approaches to reduce human errors and deviations from standard ways of work. Previous ED studies were mostly focused on observing cases of performance adjustment from 'work-as-done (WAD)' and interpreting what resilience means in the field of emergency care. In order to induce a transition from the case-based to the model-based approach, this paper offered four common patterns of performance adjustment in the EDs and represented such patterns in five different conceptual models of resilience. These models show promise in representing how the EDs deal with excess demands and can shed light on context-specific technological or procedural interventions that aim to resolve prevalent issues in the EDs. As promising areas for such interventions, strategies for ED resilience presented in this paper should be further examined, developed or tested.

Declaration of Competing Interest

The authors have no interests to declare.

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