Vive la diversité! High Reliability Organisation (HRO) and Resilience Engineering (RE)

Jean-Christophe Le Coze

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Jean Christophe Le Coze
Institut National de l'environnement industriel et des risques
Parc Alata
60550 Verneuil en Halatte
Phd

Telephone 0033 (0)3 44 55 62 04
Email jean-christophe.lecoze@ineris.fr

Suggested reviewers

Kathleen Sutcliffe
ksutcliffe@jhu.edu

Erik Hollnagel
Erik.hollnagel@gmail.com

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High Reliability Organisation (HRO) *AND* Resilience Engineering (RE)

Abstract

High Reliability Organisation (HRO) and Resilience Engineering (RE) are two research traditions which have attracted a wide and diverse readership in the past decade. Both have reached the status of central contributions to the field of safety while sharing a similar orientation. This is not without creating tensions or questions, as expressed in the call of this special issue. The contention of this article is that these two schools introduce ways of approaching safety which need to be reflected upon in order to avoid simplifications and hasty judgments about their relative strength, weaknesses or degree of overlapping. HRO has gained strength and legitimacy from (1) studying ethnographically, with an organisational angle, high-risk systems, (2) debating about principles producing organisation reliability in face of high complexity and (3) conceptualising some of these principles into a successful generic model of "collective mindfulness", with both practical and theoretical success. RE has gained strength and legitimacy from (1) harnessing then deconstructing, empirically and theoretically, the notion of 'human error', (2) argued for a system (and complexity) view and discourse about safety/accidents, (3) and supported this view with the help of (graphical) actionable models and methods (i.e. the engineering orientation). In order to show this, one has to go beyond the past 10 years of RE to include a longer time frame going back to the 80s to the early days of Cognitive Engineering (CE). The approach that is followed here includes therefore a strong historical orientation as a way to better understand the present situation, profile each school, promote complementarities while maintaining nuances.

Introduction

Safety can be an intriguing topic for researchers, practitioners and outsiders. As much as for the study of 'science', it is approached by an array of disciplines with very diverse orientations, and across industries (Le Coze, Pettersen, Reiman, 2014). From an academic point of view, if one uses publications and births of journals as an indication, safety as a scholarship topic is not a very old endeavour (e.g. Hale, 2014). It is about 30 to 40 years old. Reflecting on its origins and journey is today arguably justified by the fact that companies, states, civil societies and researchers have been facing in the past years major changes revolutionising our lives: globalisations processes including accelerated technological developments coupled with new ecological awareness of our relationship with nature which trigger needs for a renewal of our established worldviews (Atlan, Pol Droit, 2014).

The world has indeed been evolving in the past thirty years under processes of globalisation and ecological awareness. This has not been without creating new contexts for high-risk systems. Regulations, civil society, nation states, private and public organisations, labour, workforce and new technological capabilities have indeed evolved to shape new operating constraints. Keeping

in mind the nuances, namely understanding the degree of overlapping but also nature and reasons of differences anchored in disciplines and research traditions, help keep track and maintain a broad sense of the transformations which affect several layers or dimensions of safety critical operations. Rich and interesting pictures start to take shape when keeping these nuances in mind.

High Reliability Organisation (HRO) and Resilience Engineering (RE) are two of these research traditions rooted in different histories, disciplines, networks and intellectual styles promoted by authors from US and Europe. These two schools attracted a wide and diverse readership and both reached the status of central contributions to the field of safety. But it is not without creating tensions or questions. RE is introduced as a 10 years old movement and seems to promote similar orientation than HRO which is 30 years old, so, what's new here? What are their differences? Why using new vocabulary for tackling similar phenomena?

In this article, I come back on thirty years of development indicating key authors and key contributions on both side of HRO and RE. It is interesting to note that what is now explored here with the special issue of Safety Science to confront the two schools could have taken place earlier. The two schools have acknowledged each other very early on in the 80s then subsequently. It is however only in the current context that more explicit explorations seem to be required.

I want to warn immediately that any historical retrospective such as this one, using only a restricted amount of space, entail at least two types of simplifications of the past. First, it has to restrict, in the text, to a certain degree the level of depth of the empirical, methodological and conceptual developments in each school. Second, it must also restrict the presentation of the range of intellectual sensitivities between the selected authors within the 'boundaries' of two research traditions such as HRO and RE. These two schools include indeed a range of authors who, despite being grouped under the banner of one camp, HRO or RE, have slightly different interests and theoretical orientations.

La Porte, Roberts, Rochlin and Weick are names associated with the HRO history, each with slightly different approaches and interests because of their backgrounds (e.g. social psychology, political science, organisational psychology, history). Rasmussen, Reason, Woods, Hollnagel or Leveson are main authors associated with the development of RE, and here again, they have each their own stances (e.g. psychology, ergonomics, cognitive engineering, system safety). This article does not delve into this level of detail because of space constraints although the reader needs to keep this in mind.

Despite this diversity of authors and specificities, I want nevertheless to characterise what bind them in both research traditions in order to reach the level of generality needed to better delineate two different orientations, one, RE, rooted in the movement of engineering, human factors, ergonomics and cognitive (system) engineering, the other, HRO, in the social sciences, more specifically social psychology, organisational psychology, sociology and political sciences. Finally, I suggest that it is also appropriate to consider looking into the complementarities of the two schools for the study of high risk systems.

The guiding idea behind this article is that we should celebrate diversity in styles, methods, concepts and purposes in the field of safety even if it requires at times for authors involved

helping outsiders, scholars or practitioners, to see the bigger picture. I don't see this situation as a sign of a poor status of a scientific 'discipline' but a sign instead of its vitality, hence the Feyerabenesque title (Feyerabend, 1975) of this article: "Vive la diversité!" I would like, to end this introduction, to reassert that exploring the relationship between HRO & RE is an opportunity to reflect upon safety as a practical, scientific and academic field more generally. It opens a window of opportunity to investigate the diversity of possible approaches to safety, and helps reveal preconceptions that one needs to be aware of when involved in safety research. Although central, RE and HRO are not the only research traditions in the field.

For this purpose, I proceed as follows. In a first section, I indicate main authors, arguments, debates, articles and books produced in each school[1]. It is in this section that RE will be explicitly linked to the history of human factors (HF) and cognitive (system) engineering (CE) from which it derives directly. The idea behind this historical approach is to show that the two schools developed in parallel to each other, with a certain degree of autonomy shaped by different orientations and disciplinary backgrounds over the past 30 years. This is clear when proceeding historically, but, because the two stories are rarely put together, it is not always obvious to researchers.

The reason for this is specialisation. One knows very well his or her field (e.g. cognitive engineering or organisational theory) but not always very much beyond. Socialisation within the paradigms of disciplines, Universities, journals, publications and cognitive costs of moving from one field to another are elements of explanation. The main purpose of this article is therefore to overcome this situation and lay out very clearly these two histories. This first step provides therefore the background and material for the second section which consists in analysing and comparing some selected aspects of the two schools as well as their relationships. A final section elaborates further on the conceptual, practical and axiological diversity of the two schools.

Histories

High Reliability Organisations

Origins, initial empirical and theoretical insights

The story of the HRO school is now fairly well known in the safety literature. La Porte, a political scientist (La Porte, 1975), produced the core research program in a chapter by formulating the problem of 'nearly error free' operations (La Porte, 1982), in a book edited by social scientists following TMI (1979). Together with Roberts, an organisational psychologist (Roberts et al, 1978) and Rochlin, a physicist with a historical and social approach to technology (Rochlin, 1974), they spent few years, from the mid 80s onwards, carrying out ethnographic work to address the theoretical issue of 'nearly error free' operations. How can personnel of high-risk systems, such as nuclear power plants, learn when mistakes are not permitted? Whereas trial and error is a welcome strategy, desirable for one to progress in many areas of social life (e.g.,

[1] To reassert it, I can only be superficial when it comes to introducing concepts given space constraints but this special issue of Safety Science certainly requires a minimum degree of reader's familiarity with at least one of the two schools. If not, readers are advised to select some articles indicated below (table 1), delve into them then come back to this article.

education), the consequences of making errors in these safety critical artefacts would entail such potential consequences that it has to be, somehow (that is the question), strictly limited.

How does this "nearly error free" requirement translate concretely in daily mode of operations? What are the processes which support safe operations? Paul Schulman, a political scientist (Schulman,), Karl Weick, a socio-psychological scientist (Weick, 1979) but also a bit later Mathilde Bourrier, an organisational sociologist, joined the group's endeavour (Bourrier, 1999, 2001). Within 10 to 15 years during the 80s and 90s, a series of communications, chapters, articles, and books, were produced to delineate the contour of what has become this research tradition.

Produced collectively (e.g. La Porte, Rochlin, Roberts, 1987, La Porte, Consolini, 1991, Roberts, 1993, La Porte, Rochlin, 1996a, 1996b, Roberts, Rousseau, 1989, Grabowsky, Roberts, 1997, 1999, Weick, Sutcliffe, Obstfeld, 1999, Bourrier, 2001, Weick, Sutcliffe, 2003) or individually (e.g. Roberts, 1989, 1990, 1993, Weick, 1987, 1989, 1990, 1993, Schulman, 1993a, 1993b, Rochlin, 1989, 1993, 1999, Bourrier, 1999), these pieces introduced outcomes and defined concepts but also sources of tensions and debates. The journals where this body of work has been published include primarily Journal of Contingencies and Crisis Management, Organization Science, Public Administration, Administrative Science Quaterly, California Review of Management but also, more recently, Journal of Organizational Behaviour.

One important aspect of this research is that studying empirically operations of high risk systems convinced many of these researchers about the theoretical developments needed to apprehend these operations. Aircraft carriers, nuclear power plants and air traffic control stood apart from established organisational theory (e.g. Scott, 1981) because of their complex modes of operating and unforgiving technological and socio-political contexts. One contention was that what was available in the literature was inadequate to address the complexities observed, hence the need for ad hoc developments.

This is particularly clear in Roberts (1989, 161) *"For a variety of reasons the organizational literature fails to deal specifically with either hazardous organizations or with the subset in that category which might be defined as engaging in extremely high levels of performance reliability"* (Roberts, 1990). La Porte, Roberts, Rochlin and Weick elaborated this rationale by stressing the strong cognitive and social requirements entailed by these operations.

A series of concepts, now well known in the field, were established to frame and theorise observations for the purpose of understanding the production of high-reliable operations: 'self-adaptive features of networks', 'having the bubble', 'heedful interactions', 'attention to failures and learning', 'socialising processes emphasising safety', etc. They capture these sociocognitive processes established in daily interactions sometimes across hierarchical structures of organisations. One example is the specific dynamic and temporal property observed in several different settings (e.g., air traffic control, aircraft carrier).

Observations indeed show how patterns of interactions depend on contextual features of situations, triggering reconfiguration of, for instance formal authorities, to satisfy real time problem solving capabilities. These micro-meso layers of analysis were also complemented by macro interests about the challenges of both regulatory and civil society demands, raising issues of institutional trust and transparency (La Porte, Rochlin, 1996a). The approach was clearly

multidimensional, reflecting both the diversity of researchers' backgrounds and reliability/safety as an object of investigation.

One could not introduce HRO without mentioning the central debate about Charles Perrow's thesis (Perrow, 1984) that tight coupling and high complexity could lead to 'normal accidents'. If HRO researchers found little in the organisational literature to interpret their empirical findings as explained above, one exception was Perrow's contribution[2].

But it was a retrospective approach, and was not based on empirical studies conducted by the author himself, but secondary data. It provided nevertheless a background to discuss observations and concepts of the Berkeley group. Despite their reluctance to see themselves as the official opponents to the 'Normal Accident' thesis (e.g. La Porte, Rochlin, 1996b), both Sagan and Perrow argued otherwise (Sagan, 1993, Perrow, 1996) and this fed an intense debate echoed in the organisational literature more widely (Scott, 2003).

Although this opposition has simplified the many nuances of the HRO tradition (see for instance the proposition of 'reliability seeking organisations' by Rochlin, 1993), it also created the conditions for delineating a new field of investigation more broadly within social sciences (and particularly organisational theory), with its own empirical, methodological and conceptual issues. The wave of disasters of the 80s (Chernobyl, 1986, Challenger, 1986, Bhopal, 1984, Piper Alpha, 1988, etc) amplified the managerial, social and political relevance of these studies and debates.

Establishing practically and theoretically the centrality of "mindfulness"

In this context, the book from Karl Weick and Kathleen Sutcliffe (Weick, Sutfcliffe, 2003) following an earlier article in 1999 (Weick, Sutcliffe, Obstfeld, 1999) served as an important platform for these ideas beyond scholars. Operators, managers and regulators in a diversity of high-risk or safety critical organisations including fire fighting, healthcare or petrochemical industry found interest in the properties of high reliability for managerial and regulatory purposes. Combining five processes in the integrative and conceptualised framework of 'collective mindfulness', the authors established indeed a generic model with a normative flavour that, beyond empirical domain, appealed to a wide audience. This side of the HRO tradition is not without triggering concerns among researchers who have different axiological postures.

Should researchers also be consultants or remain as far as possible outsiders? Should they be independent observers who should remain very cautious about any recipe but also any implications, any unintended effects that their work could trigger? Bourrier aptly refers to this tension about the two different postures "*The HRO literature has continued to grow, evolving from a research topic to a powerful marketing label (. . .) This was never the intention of the Berkeley researchers*" (Bourrier, 2011, p. 12). This however, never turned into an open debate between researchers, at least, openly in the literature. Of course, I certainly simplify the situation a bit as, first, HRO researchers were close to managers of the organisations that they were investigating.

[2] The fact that Perrow, a leading author in organisational sociology (Perrow, 1970, 1986), had to develop specific analytical lenses for understanding disasters (for an overview see Le Coze, 2015a) only reinforced the idea that these kinds of organizations stood apart from what was already available in the literature.

One finds mentioned a series of workshops held between the Berkeley team and the different managers of the systems studied (Roberts, Rousseau, 1989), and the link with management science exists also early on with Roberts then Weick who are both affiliated to management departments. Second, HRO did not stop and can't be reduced to "collective mindfulness". There have been more studies published with first hand empirical data (e.g. Roe, Schulman, 2008)[3]. However, the status of "collective mindfulness" with its generic and normative side appealed very much to practitioners, hence its success.

But this practical success (that led HRO in health care successfully, Sutcliffe, 2011), should not hide what is a sustained theoretical agenda pursued by its promoters and followers with the central concept of mindfulness (e.g. Weick, Sutcliffe, 2006, Weick, Putman, 2006, Sutcliffe, 2011, Vogus, Sutcliffe, 2012, Vogus, Rothman, Sutcliffe, Weick, 2014, Weick, 2015). Exploring a view of cognition through a different theoretical option than, among other, the once dominant information processing metaphor (Weick, Sutcliffe, 2012), mindfulness has become one central feature grasping the processes by which one's mediations with the material and social world are consciously reflected.

This constitutes a nexus of intellectual investigations into properties of high reliability, where, first, a closer link to the field of organisational behaviour (OB) is established (e.g., Waller, Roberts, 2003, Ramanujam, Rousseau, 2006, Goodman, Ramanujam, Carroll, Edmondson, Hofmann, Sutcliffe, 2011), second, a dialogue between Western and Eastern sensitivities on mindfulness is explored (e.g., Weick, Sutcliffe, 2006, Weick, Putman, 2006), and, third, the notion of mindful organising is advocated in relation to organisational mindfulness and emotion (e.g. Vogus, Sutcliffe, 2012, Vogus, Rothman, Sutcliffe, Weick, 2014).

Summary of HRO history

HRO is a research tradition established in US in the 80s on the basis of empirical studies of high risk systems at a time when no one had neither observed nor conceptualised these issues, apart from the influential 'normal accident' thesis of Charles Perrow which laid out, based on a retrospective methodology, the background for subsequent heated debates. Cumulative strategy of articulating together insights gathered from this tradition (and beyond) led to the model of 'collective mindfulness' formulated first in an article then in a book offering a generic and normative interface to a wider audience.

This research tradition is rooted in organisational theory and political sciences. So, HRO has gained strength and legitimacy from (1) studying ethnographically, with an organisational angle, high-risk systems, (2) debating about principles producing organisation reliability in face of high complexity and (3) integrating some of these principles into a generic model of "collective mindfulness", with both practical and theoretical implications. I now turn to the history of Resilience Engineering.

Resilience Engineering

The story of RE is inseparable from cognitive (system) engineering (CE), as much as human factors and (cognitive) ergonomics (HFE) and system safety engineering (SSE). Many of these fields (human factors, system safety engineering) are several decades old (mid 20th century) but

[3] For a review of HRO related literature between 2001-2007, see Roberts (Roberts, 2009).

the field of cognitive engineering is about 30 years old. This story is also fairly known for readers and researchers in the area of safety. Rasmussen, and engineer, is one of its founders throughout the 80s and 90s, along threads with Reason, Woods and Hollnagel, all psychologists. The core program of this school is to be understood in relation to engineering (or design), risk assessment purposes and to the topic of human error.

Rasmussen and Reason are the two early leading authors in this respect then followed by Hollnagel and Woods. In the 60s and 70s, the use of computers increased demands for recommendations about design of human-machine interfaces. Rasmussen was a pioneer studying human error and cognition in the prospect of establishing these recommendations (Rasmussen, 1969, 1974, Rasmussen, Jensen, 1976). Reason was also an early researcher on the understanding of errors (Reason, Micielska, 1982).

Human error: from the 'Old Look' to the 'New Look'

Post TMI (1979), this topic became the centre of attention of an international community of researchers mixing engineers, psychologists and cognitive scientists (a NATO conference in 1982 launched this dynamic, Senders, Moray, 1991). Two things are worth mentioning in the bulk of articles and books published in the 80s and 90s. First, one can distinguish two orientations, a taxonomic and a naturalistic option (Le Coze, 2015b). The former was established by Reason, and finalised in his seminal book 'Human error' (Reason, 1990). The principle consists in allocating 'failure modes' by discriminating cognitive processes in relation to type of errors (i.e. slips, lapses, mistakes, violation).

One consequence in terms of design and prevention is to try to eliminate errors likely to lead to undesirable consequences. The latter option is naturalistic because errors are seen as part of an 'ecology of action', namely an adaptive and exploratory side to cognition. In this view, errors are produced but also very often compensated by operators in real life situations[4]. They are intrinsic to learning and the ability to adapt within specific work constraints. In terms of design recommendation and preventive strategy, interfaces should be flexible to provide ample ability to operators or pilots to deal with this adaptive and exploratory side to cognition. Moreover, errors should not necessarily be the target of decontextualised retrospective judgment (i.e. hindsight bias) and not necessarily eliminated given their adaptive properties.

Errors are indeed highly relative in this latter option: "*to optimize performance, to develop smooth and efficient skills, it is very important to have opportunities to perform trial and error experiments, and human errors can in a way be considered as unsuccessful experiments with unacceptable consequences. Typically, they are only classified as human errors because they are performed in an 'unkind' environment. An unkind work environment is then defined by the fact that it is not possible for a man to observe and reverse the effects of inappropriate variations in performance before they lead to unacceptable consequences. When the effect of human variability is observable and reversible, the definition of error is related to a reference or norm in terms of the successful outcome of the activity"* (Rasmussen, 1982).

[4] This approach to cognition for the study of errors confronts scholars to methodological and epistemological problems when assessed against the normative background of experimental psychology, which requires controlled settings.

Rasmussen, Duncan, Leplat (1987), Rasmussen (1990a), Hollnagel (1983, 1993), Woods (1988), Cook, Woods (1996), Woods and Cook (1999, 2003), Amalberti (1996) and Woods et al (1994) have been pursuing and refining this deconstruction of the notion of error in the spirit of the naturalistic thread throughout the 90s. Their contention is that it is as interesting, and probably more efficient, to concentrate on expertise, namely the ability of individuals to cope with complexity, rather than on 'their' errors (Rasmussen, Lund, 1981, Woods, 1988), something that was also coined as the 'reliability of cognition' (Hollnagel, 1993)[5]. Note that it is a perspective that Reason rallied also later (Reason, 2008).

Applied and theorised from real case studies in medical, aviation and nuclear fields, this 'New Look' of error as it has been described (Woods, Cook, 2003), was then successfully deployed in accident investigation contexts (Dekker, 2002, 2004). It is as a consequence essential here to add that these developments have been produced with the prospect of providing practical solutions to engineers in the field of human reliability assessment HRA (Hollnagel, 1998) as much as for recommendations to designers of interfaces and also professional investigators dealing with interpretation of 'human errors' (e.g. aviation domain, and pilots/crew errors), hence the notion of cognitive 'engineering'.

This proximity with the worlds and issues tackled by engineers (or investigators) is entirely constitutive to the background of this school: producing methods, tools and concepts understandable by practitioners. The implications of this 'New Look' of errors, proposing the notion of variability instead, has therefore been built, argued and advocated in multiple books, chapters of books and articles in journal like Human Factors, International Journal of Man Machine Interaction, Reliability Engineering and System Safety, Safety Science, Cognition, Technology and Work, Ergonomics, Theoretical Issues in Ergonomics, over the past the thirty years.

System Safety and Complexity

The deconstruction of the notion of human error by this network of authors is therefore the first aspect constitutive of the RE movement. The second goes in hand with a system view of safety and accident complementing this critic. Reason, relying on other authors including Turner (1978) or Perrow (1984), argues for the notion of latent errors, contrasting sharp and blunt ends. Accidents are not produced locally by front line individuals (sharp end), but by 'errors' made earlier by higher decision makers (blunt end). The well known defence in depth model (later called 'Swiss Cheese') graphically and successfully helps convey this idea (Reason, 1990), and then later refined (Reason, 1997).

Rasmussen also develops a system (or one should say 'complexity') model of safety and accident by translating his findings on cognition to organisation, and proposing the concept of migration coupled with the principle of 'defence in depth fallacy' (Rasmussen, 1997), which will be found applied later through the notion of 'practical drift' by Snook (Snook, 2000) and 'resonance' by Hollnagel (Hollnagel, 2004). Anchored in adaptive and self-organised properties of complex

[5] These authors were also actors of the Naturalistic Decision Making (NDM) studies, which were developed in the end of the 80s then in the 90s (Klein et al, 1993, Klein, 1997). One understands now that the principle which consists in studying daily situations as opposed to error (or incident or accidents) is not exclusive to HRO but also advocated by CE (and NDM) as the same period of times, in the 80s/90s, at a micro, cognitive, level.

systems as conceptualised by cybernetics in the 50s and 60s (Ashby, 1956), Rasmussen's model of migration framed for the years to come the underlying assumptions of RE. His sociotechnical view (Rasmussen, 1997) has also been a strong source of inspiration for Leveson, and used as a graphical support for system safety engineering, and the STAMP method (Leveson, 2004, 2012).

So, RE rests on a Rasmussen's view of adaptive entities producing self-organised patterns through tradeoffs in a space of resources and constraints (within an envelope), something formalised further with the help of the 'complex adaptive system (CAS)' language by Woods (2015), and by Dekker relying more on the metaphorical and epistemological side to complexity in relation to accidents (Dekker, 2004, 2011). Complexity ideas are also explored with strong practical purposes by Hollnagel (2004, 2009, 2012, 2014) and the FRAM method.

In this respect, it is worth noting that Hollnagel's cycle of producing concepts coupled with the development of tools and methods is consistent over 30 years of research (Hollnagel, 1993, 1998, 2004, 2009, 2012, 2014), illustrating perfectly the engineering orientation of this school[6]. The RE book in 2006 (Hollnagel, Woods, Leveson, 2006), and subsequent books (e.g. Hollnagel, Nemeth, Dekker, 2008) are therefore the products of this legacy of human error deconstruction, system safety (complexity) and engineering orientation.

Summary of RE history

RE is a research tradition which has grown out of the activity of a network of authors who have contributed from the 80s onward to conceptualise the problem of human error as well as introduce it in the context of producing recommendations to designers of human-computer interface and to engineers performing human reliability assessment. It also proved highly relevant to investigators of accidents in various safety critical contexts (e.g. healthcare, aviation, nuclear) when the implication of the 'hindsight bias' was made explicit in relation to this deconstruction of human error.

The 'New Look' error, based on a naturalistic view and extended to a system safety/accidents approach initiated by the groundbreaking contribution of Reason (1990, 1997) and Rasmussen (1990a, 1997), found many refinements in the 90s and 2000s by authors who maintained the engineering orientation (e.g. producing practical concepts, tools and methods) for a diversity of purposes (designing, assessing, investigating).

These refinements could rely more and more on ideas coming from the field of complexity which increased popularity in the 90s and 2000s (e.g. Waldrop, 1994, Lewin, 1994, Mitchell, 2009). So, RE has gained strength and legitimacy from (1) harnessing then deconstructing, empirically and theoretically, the notion of 'human error', (2) argued for a system (and complexity) view and discourse about safety/accidents, (3) and supported this view with the help of (graphical) actionable models or methods (i.e. the engineering orientation).

[6] This side to the school has regularly triggered concerns about the status this newly created 'discipline' (e.g. Reason, 1998), is it a new science? Is it instead an engineering practice?

Comparing HRO and RE

In this section, with the help of a series of tables (tables 1, 2, 3 and 4), I analyse these two parallel histories, I indicate the common themes, exchanges but also the differences between the two schools in order to sketch their profiles.

Two parallel histories with a fair degree of independence

Coming back on a history of the two schools had the purpose of providing a background and some material for discussions. First, it is interesting to notice that the two schools produced articles, books and chapters in parallel for the past 30 years. Tables 1 & 2 illustrate this. Key articles, book chapters and books by a diversity of authors from different backgrounds in different journals were released to frame the issue of safety along the line that have been summarised in the sections above.

Table 1. Selection of books and key articles

	High Reliability Organizations (HRO)	**Cognitive (system) engineering (CE) & Resilience Engineering (RE)**
1980	*On the design and management of nearly-error free organizational control systems* (La Porte, 1982) – Book Chapter *The self-designing high-reliability organization : aircraft carrier flight operations at sea* (Rochlin, La Porte, Roberts 1987) - Article *New challenges in organisational research: high reliability organizations* (Roberts, 1989) - Article *Culture of high reliability* (Weick, 1987) - Article *Mental models of high reliability systems* (Weick, 1989) - Article *Informal organizational networking as a crisis avoidance strategy: US naval flight operations as a case study* (Rochlin 1989) - Article	*Coping with complexity* (Rasmussen, Lind, 1981) - article *Human errors. a taxonomy for describing human malfunction in industrial installations. (Rasmussen, 1982)* - Article *Absent-minded? The psychology of mental lapses and everyday errors.* (Reason, Micielska,1982) - Book *Coping with complexity: the psychology of human behaviour in complex systems* (Woods, 1988) - Chapter *Cognitive systems engineering: New wine in new bottles* (Hollnagel, Woods, 1984) - Article *New technology and Human Error* (Rasmussen, Leplat, Duncan, 1987) - Book *Why do complex organizational systems fail?* (Rasmussen, Batstone, 1989) - Report
1990	*Working in practice but not in theory: the challenges of "high reliability organizations"* (La Porte, Consolini, 1991) -Article *New challenges in understanding organizations* (Roberts, 1993) - Book *Defining 'high reliability" organizations in practice: a taxonomic prologue* (Rochlin, 1993) - Chapter	*The role of error in organizing behavior; Human Error and the Problem of Causality in Analysis of Accidents* (Rasmussen, 1990a, 1990b) - Articles *Risk management in a dynamic society : a modelling problem* (Rasmussen, 1997) - Article *Behind Human Error*: *cognitive system, computers and hindsight* (Woods,

	Mann Gulch disaster: The collapse of sensemaking (Weick, 1993) - Article *Heedful interactions (Roberts, Weick, 1993) - Article* *Collective Mindfulness* (Weick, Sutcliffe Obstfeld, 1999) - Article *Risk mitigation in virtual organizations* (Grabowski, Roberts, 1999) – Article *Le nucléaire à l'épreuve de l'organisation* (Bourrier, 1999) - Book	Johannesen, Cook, Sarter, 1994) - Book *Human Reliability Analysis: and Control, Cognitive Reliability and Error Analysis Method: CREAM.* (Hollnagel, 1993, 1998) - Books *Human Error* (Reason, 1990) - Book *Managing the risk of organisational accidents* (Reason, 1997) Book *La conduite des systèmes à risques* (Amalberti, 1996) - Book
2000	*Organiser la fiabilité* (Bourrier, 2001) - Book *Managing the unexpected* (Weick and Stucliffe, 2003) - Book *Learning from high reliability organisations* (Hopkins, 2009) - Book *High reliability management* (Roe, Schulman, 2008) – Book *Mindfulness and the quality of organizational attention* (Weick, Sutcliffe, 2006) – Article *Information overload revisitied* (Weick, Sutcliffe, 2012) *The affective foundations of high-reliability organizing* (Vogus, Rothman, Sutcliffe, Weick, 2014) – Article	*Risk management in a dynamic society (*Rasmussen, Svedung, 2000*) - Book* *Barriers and prevention, ETTO, FRAM, Safety I & II* (Hollnagel 2004, 2009, 2012, 2014) - Books *Resilience engineering* (Hollnagel, Woods, Leveson, 2006) - Book *Investigating human error, Ten questions about human errors, Just Culture, Drift into failure* (Dekker 2002, 2004, 2007, 2011) - Books *The Human Contribution: Unsafe Acts, Accidents and Heroic Recoveries* (Reason, 2008) - Book *Engineering a Safer World* (Leveson, 2012) - Book

Table 2. Disciplines & journals (selection)

	HRO	**Resilience Engineering**
Disciplines	Organisational psychology Management science Social psychology Sociology Political science System approach	Engineering Cognitive (system) engineering, Ergonomics Psychology Cybernetics, system & complexity science
Journals (selection)	Journal of Contingencies and Crisis Management Journal of Public Administration Research and Theory	Human Factors Safety Science Ergonomics Cognition, technology and work

	Organization Science Administrative Science Quarterly California Management Review Journal of Organization Behaviour	Reliability Engineering and System Safety Theoretical Issues in Ergonomics International Journal of Man Machine Interaction

Thus, when HRO authors were studying aircraft carriers, air traffic control and nuclear power plants in the 80s, CE authors were conceptualising the problem of error and its implication for interfaces design in nuclear, aviation[7] and medical contexts. When HRO debated about the outcomes of their investigation in relation to the thesis of Normal Accident in the 90s, CE refined the naturalistic side to cognition and expanded safety towards system and complexity[8] views while developing tools and practical guidance to a range of actors (risk assessment engineers, designers of interfaces, and investigators of incidents/accidents).

When the HRO tradition produced the model of "collective mindfulness" in the 2000s, cognitive engineers turned to the notion of Resilience Engineering to emphasise further the naturalistic and positive side to cognition of these front line actors which are behind the production of safety[9]. The next table (table 3) extracts, from the above short histories, the key topics and debates which have been shaping the content and directions of research in the two schools.

Table 3. Selected key topics and debates

	HRO	**Resilience Engineering**
Key topics/themes	'Nearly error-free' operations Interdependence, redundancy and slack Training, socialisation & culture Collective Mindfulness & Sensemaking Flexible (self-adapting) structure & networks Institutional trust	Human machine (computer) interface Human error (including 'hindsight bias'), reliability of cognition & resilience Situation awareness & expertise (Naturalistic Decision Making) System Safety & Accident Models Adaptation, Self organisation & Complexity

[7] Note that CRM (Crew/Cockpit Resource Management) is derived from human factor background in the 80s (Flin, 1996, Flin, Crichton, Connor, 2008).

[8] Of course, HRO works are based on system approach which strongly structured the field of organisational theory in the 60s onward (Scott, 2003), but it has been conceptualised, in particular complexity, in the two schools differently.

[9] In the field of safety, resilience had been used earlier, for instance by Wildavsky (1988) and Weick (1993). These authors oppose resilience to anticipation, a definition that is not incompatible with RE, but only partly overlapping (see overview by Woods, 2015). Resilience in RE shifts the focus from the negative side of error to variability, adaptation, trade-offs and expertise produced in daily activities.

Key debates within tradition	Normal Accident and HRO Status of high-risk systems in relation to organisational theory Descriptive or normative posture of HRO descriptions (covert debate)	Taxonomic/naturalist approach to human error Status of discipline as science or engineering Studying cognition in real life outside experimental psychology

On the HRO side, topics include 'nearly error-free' operations; interdependence, redundancy and slack; training, socialisation and culture; collective mindfulness, resilience and sensemaking; flexible (self-adapting) structure and networks; institutional trust. On the RE side, one can consider the following ones: human machine (computer) interface; human error, reliability of cognition, resilience; situation awareness and expertise (naturalistic decision making); system safety (& accident) models; adaptation, self organisation & complexity. As it appears in this list, there are overlapping areas in both traditions, without being able to say which one was 'first' or would be now more 'legitimate' than the other. If they express different angles and styles they however also offer corresponding concepts. I now comment two of these obvious cases.

Situation awareness - having the bubble

One that comes to mind is "situation awareness" from the developments of the CE school (e.g. Woods, Sarter, 1994) and "having the bubble" from the HRO tradition (Roberts, Rousseau, 1989). In the field of human factors and cognitive engineering, the notion of "situation awareness" is at the heart of concrete practical methods, tools and concepts to train pilots and assess situations against the risk of errors. In this perspective, errors are understood as the products of problems of situation awareness. It characterises this specific moment when an individual fails to interpret adequately circumstances of complex dynamic environments, and provoke unwanted outcomes.

This idea is mirrored by the principle of 'having the bubble' in the HRO tradition (Roberts, Rousseau, 1989), which is derived from observations of real life situations. By keeping sight of what's going on through a constant updating of the big picture, experienced individuals manage to supervise and steer complex coordinated activities across functions during real-time daily operations. They both, "situation awareness" and "having the bubble", relate to the ability of maintaining an appropriate picture of situations to perform safe operations, whether this is in the case of an aircraft pilot (or crew), or in the case of an aircraft carrier officer on deck in charge of keeping sight of coordination of tasks among a diversity of individuals. These two are actually grouped under the category of "sensitivity to operations"in Weick, Obstfeld and Sutcliffe (1999) as one process out of 5 in the model of "collective mindfulness".

Self-organising - self-designing - self-adapting

Another example is the self-organised or self-designing features of high-risk systems that are recognised very early on in both traditions as an important feature to grasp. In CE, it derives from an empirical and conceptual investigation at a micro level (Rasmussen, Jensen, 1974, Rasmussen, 1976) turned into a macro one (Rasmussen, 1990a, b) and in HRO, it is inferred from fieldwork describing dynamics of informal networks (Roberts, Rochlin, La Porte, 1987,

Rochlin, 1989). This recognition of the importance of self-organisation is made explicit in the following quote from Rasmussen when bridging the two traditions back in the 80s, in 1989.

"Rochlin characterises the relationships between technology and organisations with respect to complexity, error, and risk against the background of the influential studies of the Berkeley group of the evolution of the high-reliability organisation of an American aircraft carrier. Even if the context is that of a social science study, the notions used to analyse the organisation in evolutionary and 'self-designing' terms often mirrors concepts of cybernetic theories of self-organisation (e.g. Ashby's requisite variety)" (Rasmussen, 1989)'.

A very good example of this today is Roe and Schulman HRO empirical description of self-adaptive cognitive dynamics of what is described as "reliability professionals" (Roe, Schulman, 2008) which is then combined, later, with RE influences by Patterson and Wears (2014). In the two schools, notion of 'self' whether 'organised', 'adaptive' or 'designing' systems can be both positive and negative (in the "collective mindfulness" model, it was originally covered by the notion of 'underspecification of structures' which became 'deference to expertise', Weick, Obstfeld and Sutcliffe, 1999). Positive when it promotes flexible responses in daily operations and to critical situations (e.g. resilience), negative when it generates unexpected patterns leading to unwanted events (e.g. defence in depth fallacy, drift, resonance).

Exchanges between the two traditions

Sometimes, concepts are also borrowed from one tradition to the other in order to serve argument. Weick's cognitive approach through constructivist, sensemaking and interactionist lenses appealed to CE and RE authors with an interest for retrospective account of events, as for Dekker (2004). He found in Weick a support for an alternative view to information processing applied to cognition. In the context of accident investigation, this proved highly relevant (Dekker, 2002, 2004).

Thus, because of this proximity of interests, explicit references between traditions are often found. In this respect, the cognitive side to HRO (with the concept of mindfulness) and RE create indeed strong links between the two traditions (e.g., the indications above about the model of "collective mindfulness"). However, it remains important to stress nuances, even when two cognitive approaches are advocated. But in order to do so and come back to this issue, it is worth turning to differences, because, of course, there are also differences.

Differences between the research traditions

For instance, socialisation, culture or institutional trust are topics which are not explored in CE and RE, and human-machine interfaces with recommendations or specifications for designers is not really studied in HRO. This derives from the level of analysis, the purpose as well as the disciplines of origins. This is not without implications. A psychologist or a cognitive scientist is not a sociologist. Their knowledge differs. This is an obvious statement but one with real implications worth pondering. Let's illustrate.

A cognitive psychologist has been socialised through his studies and research to tackle a range of different topics as for instance memory, attention, perception, language, intelligence, problem resolution or emotion. In contrast, a trained sociologist has studied socialisation, inequalities,

organisation, labour relations, family, gender, social stratification or movements or the media. One does not conceptualise and observe brain processes of perception as one does study labour relations or social movements. Perceptions, labour relations or social movements are nevertheless potentially relevant to safety research, with different angles of analysis.

In general, methodological, empirical, theoretical and epistemological issues and backgrounds are interwoven within the paradigms of scientific disciplines which frame specific objects. As a result, and from an epistemological (or ontological) point of view, some orientations in cognitive sciences rely for instance on assumptions about human nature, the architecture of the brain and relationship with biology, assumptions that the social sciences might not share.

For many social scientists, understanding individuals implies certain assumptions regarding the unique aspects of our symbolic world that questions reductionist (e.g. biological) ambitions that some cognitive scientists might advocate to conceptualise the social (as the prefix 'neuro' translates in some recent trends, e.g., "neurosociology"). However, a vast majority of sociologists have no need and/or interest in the biology of the brain.

Conversely, a notion like power is not so much part of the conceptual background of cognitive psychologists although for social sciences it would be difficult to consider the understanding of organisation or society without explicit reference to this concept. Thus, despite some overlapping interests, table 4 characterises what could be called the 'intellectual orientations' of the two traditions, including main roots, principal layer of analysis, dominant axiological position.

Table 4. Research traditions' profiles

	HRO	**RE**
Main roots	Roots in social sciences, ethnographic approach and empirical case studies.	Roots in engineering and an ecological perspective of psychology & cognition.
Principal layer of analysis (of empirical and conceptual)	Empirical studies and conceptualisation based on a mix of micro-meso-macro (interactionist, managerial, social and political) orientation.	Empirical studies and conceptualisation mainly based on a (micro) cognitive orientation (linked to macro layers through systemic/complexity lenses).
Dominant axiological position	Driven by descriptive ambition, with a rather value neutral perspective (but this remains a covert debate) Normative component as a secondary outcome of a consulting market and industry demand.	Explicitly oriented towards practitioners (engineers, designers, front line operators, managers or investigators). Normative posture as an intrinsic feature of the engineering orientation.

These distinctions between the schools bring the nuances needed to avoid simplifications. HRO is based on the body of knowledge developed in the social sciences whereas RE has a stronger link to engineering and cognitive sciences. This difference was reflected in the kind of debates triggered in the two traditions over the years (table 3). In HRO, one issue was to question relationship with existing organisational theory whereas for CE one issue was the possibility of studying cognition in a scientific manner without relying on the principles of experimental psychology. But, in my view, this diversity is welcome.

Vive la diversité!

As introduced in this article, safety is an intriguing research topic because it is possible to investigate it from the perspective of a range of strategies whether mono, multi or interdisciplinary, whether descriptive or normative (e.g. engineering), etc. RE and HRO are very good illustrations of this, both being rather interdisciplinary but combining different disciplines, both being involved in high-risk systems but with slightly different purposes, both being empirical and conceptual but with distinct intellectual orientations. In this respect, to move from C(S)E to RE in the mid 2000s (Hollnagel, Woods, Leveson, 2006) has created ambiguities because it seemed to promote something new whereas it can also be seen in fact as a continuation of thirty years of work in cognitive (system) engineering based on a solid body of knowledge established through empirical, theoretical and practical research in the field of safety (tables 1 to 3). And, although there are overlapping domains between HRO and RE (e.g., 'situation awareness/having the bubble'; 'self organised properties'), there are also differences. In this final section, I discuss both conceptual and axiological dimensions of the two schools to illustrate the importance of keeping these nuances in mind. I conclude with indicating current and future trends of hybridisation and interdisciplinarity.

Conceptual diversity

Stressing nuances between traditions is the reason why the title of this article, "Vive la diversité!", explicitly supports the idea that maintaining diversity visible is needed because the world is (epistemologically) complex. Anyone engaged in ethnographic work of daily operations of high-risk systems has something to gain from knowing about CE and RE contribution on human machine (computer) interfaces; human error, reliability of cognition, resilience; situation awareness and expertise, system safety (& accident) models; adaptation, self organisation & complexity; AND from HRO with redundancy and slack; training, socialisation and culture; collective mindfulness, resilience and sensemaking; flexible (self-adapting) structure and networks; institutional trust.

They offer a continuum of interest from micro to macro situations to be articulated in order to grasp the complex nature of sociotechnological systems. They introduce a range of disciplines which needs to be considered when conceptualising safety. As a researcher, I have personally valued this diversity of perspectives, even on similar topics. It proves heuristically powerful, theoretically inspiring and practically useful. The message is that complementarities exist but that diversity of assumptions and preconceptions embedded in the history and foundations of disciplines need to be kept in mind to avoid the risk of conflating them.

Let's come back now on the cognitive orientations of the two traditions to illustrate this point. It is probably at this level of description that the principle of maintaining nuances of each school's profile (table 4) is the most interesting. The deconstruction of "human errors" by cognitive

psychology and cognitive engineering has provided invaluable material to understand this phenomena and interact with industry. Relying on knowledge about cognition as conceptualised in the 80s and 90s through processes of perception, memory, attention, decision making associated into models based partly on an analogy with computers, researchers could convincingly argue about the naturalness of errors.

It allowed immense improvements in the way individuals (e.g., aircraft pilots) perceived their own and other contributions to incidents and accidents but also in the way prevention of errors could be developed[10]. This was done within disciplinary boundaries and orientation of CE and RE as indicated above (table 4). For instance, distinguishing categories of errors as resulting from automatic or reflexive processes is key to many operational situations, and constitutes important input to crew resource management (CRM) programs, then towards a better appreciation of the reliability of cognition (Hollnagel, 1993) and individuals' expertise (Klein, 1997).

HRO did not operate so explicitly this deconstruction of the original common sense idea on "human error", but is strong in other areas by exploring mindfulness, which derives from other roots in social psychology and philosophy (Weick, 1979, 1995) than mainstream cognitive science relying on computer analogy and different assumption of the mind or decision making. Compare for instance, although not incompatible, the two treatments of information overload by Hollnagel (1992) and Weick, Sutcliffe (2012) which express different intellectual sensitivities. At the same time, by engaging with both the psycho-cognitive and social dimensions of mindfulness, by introducing affects and emotions and comparing Western and Eastern approaches, the mindfulness idea from HRO opens alternative paths to our grasp of operational situations in safety critical organisations.

Axiological diversity

This example also helps illustrate nuances of axiological postures between HRO and RE. The engineering orientation of CE/RE in this respect is explicitly and well captured in the following quote. "*A model that is cumbersome and costly to use will from the very start be at disadvantage, even if it from an academic point of view provides a better explanation. The trick is therefore to find a model that at the same time is so simple that it can be used without engendering problems or requiring too much specialised knowledge, yet powerful enough to go beneath the often deceptive surface descriptions (…) The consequence is rather that we should acknowledge the simplifications that the model brings, and carefully weigh advantages against disadvantages so that a choice of model is made knowingly*" (Hollnagel, Woods, 2006, 245).

It is also worth indicating that because of this orientation, many ideas from RE do not always in fact strike as very new for readers knowledgeable in safety intellectual production and beyond. It sometimes seems to reformulate already existing ideas which are borrowed without acknowledgment or clearly relating these ideas to other ones for reasons that could have nothing to do with 'pure' scientific purposes, e.g., ego, networks (Hopkins, 2014). But, in my opinion, what should be appreciated is not novelty in the academic sense of the term, but instead

[10] It is in this respect similar to Gardner psychological theory of multiple intelligences in the sense that it helped tremendously people see themselves differently, and engage teachers in new directions when it comes to education programs and understanding children's learning abilities (Gardner, 2011).

a novelty in the ability to be easily understandable to practitioners in order to help change both mindsets and practices.

"*This book is intended for practitioners rather than researchers (...) The reason for this partiality is simple – it is the practitioner who can makes changes to practice, not the academic. The intention is that the practically minded reader should be able to read the book without constantly consulting the references and even without caring much about them*" (Hollnagel, 2004, xiii). There is also this sentence translating the axiological difference "*resilience engineering is the action program of high reliability organisation"* (Woods, Dekker, 2010). It remains, of course, an open (and difficult) question to know how successful these attempts are.

As a consequence, for a researcher interested in empirical and analytical insights without the constraint of making them appealing and useful to specific practitioners, this is not necessarily important. What is is the ability to produce knowledge about phenomena with the help of scientific arguments grounded in the mastery of a discipline (e.g. political sciences) or several, and debated in scientific journals. For instance, to approach meso and macro situations of high-risk systems, the HRO tradition is very appropriate, and linked to disciplines (e.g. sociology of organisation, political sciences) which help conceptualise these layers of analysis in a way that a cognitive view does not[11].

When writing this, it becomes clear that the respective value of the two traditions depends on the problems, level of analysis and purposes of the researcher and, more generally, the users. Developments needed to support the range of practitioners in their daily operations are different from developments needed to conceptualise and compare high-risk systems through in depth ethnographic studies; although it seems reasonable to think that the two are needed. In this respect, although complementarities have been indicated between CE/RE and HRO in this article, it is also worth not forgetting about the disciplinary roots and profiles of each school[12].

Hybridisation, interdisciplinarity ... and nuances

If one considers, as introduced in this article, safety to be the product of now globalised complex sociotechnological systems, then strategies of companies resulting from managerial decision making processes, political contexts including regulation, control authorities and civil society activism, organisational structures and engineering design of technology including choices of automations and interfaces, real contexts of operators activities and tasks but also contractual relationship between collaborating companies etc need to be included in the picture. But, these topics are studied by disciplines as diverse as management science, political science, sociology of organisation and technology, cognitive engineering and ergonomics, but also engineering and law which require strategies of interdisciplinarity (Le Coze, 2016).

In fact, as illustrated above with Patterson and Wears (2014) in health care, researchers have already started to combine the two schools discussed in this paper within their own personal developments, sometimes with other influences too. Examples of interdisciplinarity or

[11] In RE, the move from micro to macro is theorised through complexity discourse, but it is, as far as know, not always empirically illustrated (e.g. Dekker, 2011).

[12] See for instance Perrow's reaction to some researchers' attempt to combine traditions irrespectively of their specificity (Perrow, 2009).

hybridisation of this sort, combining both RE and HRO with other scientific domains can be found in Haavik (2012) or Le Coze (2013) who mobilise the field of social study of science and technology (STS). Future advances and research are certainly in these kinds of hybridisations. But, if interdisciplinarity is a highly popular research incentive and practice (Barry, Born, 2013), it should not be performed without the ability to strongly reflect about nuances before aggregating insights into unified big pictures.

Conclusion

Both RE (with CE) and HRO are post-TMI products, thirty years ago. The nuclear accident of 1979 created an incentive for different communities of researchers to explore its dimensions through engineering, cognitive, psychological or social sciences, and the relevance of this endeavour was reinforced by a well known series of disasters in the 80s among which Challenger, Bhopal, Piper Alpha or Chernobyl. Authors with some early interests in related topics in the 70s, such as La Porte about the control of complex social systems and Rasmussen on human factors in relation to interface design, played key roles in shaping respectively HRO and CE, then RE programs.

Both programs, carried out, translated, developed, by researchers and teams of researchers which created active networks became leading contributions in the field of safety in the following decades. By coming back, with a certain degree of simplifications needed for this article, on the histories of these two research traditions, the purpose is to make more explicit the differing underlying intellectual orientations and contributions. By defining key articles and books, central debates and topics, but also disciplines, roots, scope and axiological orientation, a profile for each school is established. It is advocated that such diversity should be kept in mind, maintained because of our complex world but also that overlapping concepts and complementarities, called here “hybridisations”, should be favoured for ethnographic works that attempt to grasp the multidimensional nature of safety in current and ever evolving complex sociotechnological systems.

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