THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Tacit Knowledge: Nature and Transfer in Safety-Critical Systems

Application on Maritime Pilot Training

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover:
This generic illustration presents core elements from the licentiate thesis. From left to right, the elements depicted include: a framework for tacit knowledge (author), knowledge creation (Freepik), a mariner (Freepik), and a segment of the pilot passage plan for Gothenburg harbors (Swedish Maritime Administration).

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ABSTRACT

The accumulation of knowledge, intuitive understanding, expertise, and skills for managing both routine and non-routine situations develops over extended periods of time. These insights, often unspoken, deeply personal, and grounded in experience, are difficult to formalize and communicate and are commonly referred to as tacit knowledge. The departure of experienced individuals from an organization can result in significant declines in productivity, efficiency, and safety due to the loss of specialized knowledge and skills, including tacit knowledge. In safety-critical systems, the erosion of such knowledge can have severe consequences, particularly in the event of malfunctions or system failures. Therefore, the transfer of tacit knowledge is crucial in educational settings, where novices develop the knowledge and skills necessary to ensure compliance with industry standards for efficiency and safety.

This licentiate thesis aimed to evaluate the nature and transfer of tacit knowledge in safety-critical systems, with a specific focus on maritime pilot training within the context of maritime simulators. Additionally, it evaluated the use of eye-tracking as a didactic tool and its role in managing tacit knowledge within such training environments. Moreover, the licentiate thesis explored the nature of tacit knowledge, developed a taxonomy related to associated concepts, defined tacit knowledge as a framework and compared it to maritime pilot training, and proposed guidelines to enhance its transfer in such training settings.

An exploratory mixed-methods design was employed, incorporating a systematic literature review conducted in accordance with PRISMA guidelines, evaluating 22 studies on tacit knowledge transfer in safety-critical systems. In addition, a study grounded in activity theory investigated tacit knowledge transfer in maritime pilot training, involving 21 participants. A usability study further examined the application of eye-tracking as a didactic tool in simulator-based maritime pilot training, with tacit knowledge evaluations conducted on 57 participants. Data were collected through interviews, observations, questionnaires, document analysis, eye-tracking, and comparative explanatory compilations. The data analysis utilized descriptive statistical methods, inductive thematic analysis, activity theory, the SECI model, and contextual frameworks.

The findings revealed that tacit knowledge resided in various domains and faculties, making it difficult to define and operationalize. Tacit knowledge was therefore reconceptualized as a framework encompassing several interrelated components. When this framework was applied to maritime pilot training, tacit knowledge transfer was observed only partially, in social learning environments such as apprenticeships during actual pilotage, but was less evident in other areas of training, particularly in simulator sessions. In these contexts, concepts such as intuition, procedural knowledge, pattern recognition, and muscle memory were often used interchangeably but were later identified as related yet distinct. Guidelines for more effective tacit knowledge transfer included alumni functions, job rotation, mentorship programs, staff rotation, and the development of repositories to capture best practices and operational experiences. Furthermore, guidelines for conducting efficient research into tacit knowledge transfer could serve as a foundation for enhancing the training syllabus.

In conclusion, this licentiate thesis presents a comprehensive and systematic mapping and deconstruction of tacit knowledge, along with a taxonomy on the subject. This work culminates in the development of a framework to conceptualize and define tacit knowledge applicable to research on organizational learning, particularly in maritime pilot training. Furthermore, this licentiate thesis offers guidelines aimed at enhancing maritime pilot training in both organizational and research contexts.

Keywords: Tacit knowledge, systematic literature review, safety-critical systems, socio-technical systems, activity theory, SECI model, mixed-methods, maritime pilot training, simulators, eye-tracking

PREFACE

The studies presented in this licentiate thesis were conducted at the Division of Design & Human Factors, within the Department of Industrial and Materials Science (IMS) at Chalmers University of Technology, Sweden, between June 2020 and October 2023. All research was carried out as part of the project Evaluation of Eye-Tracking as Support in Simulator Training for Maritime Pilots (TRV: 2019/117837), funded by the Swedish Transport Administration in collaboration with the Swedish Maritime Administration.

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Finally, there is one person who has supported me in every endeavor I have ever embarked on, who has always believed in me and stood by me, and who has been involved in this thesis by proxy, usually at the kitchen table over a cup of coffee and a cinnamon bun: thank you, Anna-Lena—my dear mom.

Gothenburg, November 2024
Rikard Eklund

If you tell me I will listen,
if you show me I will see,
if you let me experience I will learn.

Laozi, Chinese philosopher, 600 B.C.

LIST OF PUBLICATIONS

The following publications are included in the licentiate thesis.

Paper 1
Eklund, R., Osvalder A.-L. (2024). Transferring tacit knowledge in safety-critical systems—a systematic literature review.
Submitted to Heliyon Journal for publication.

Contribution:
Eklund planned and conducted the study supported by Osvalder. Eklund wrote the paper supported by Osvalder.

Paper 2
Eklund R., Osvalder, A.-L. (2022a). Transferring tacit knowledge during maritime pilot training: assessment of methods in use, in: K. Plant, G. Praetorius (Eds) Human Factors in Transportation, *Proceedings of the 13th AHFE International Conference on Human Factors in Transportation* (pp. 665–674). https://doi.org/10.54941/ahfe1002503

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Contribution:
Eklund planned and conducted the study supported by Osvalder. Eklund wrote the paper supported by Osvalder.

ADDITIONAL PUBLICATIONS

The following publications are not included in the licentiate thesis but are however related.

Eklund, R., & Osvalder, A.-L. (2021). Optimizing aircraft taxi speed: Design and evaluation of new means to present information on a head-up display. *Journal of Navigation*, 74(6), 1305–1335. https://doi.org/10.1017/S0373463321000606

Eklund, R., & Osvalder, A.-L. (2022b). Assessing non-technical methods for transferring tacit knowledge in safety-critical systems: a study on maritime pilot training, in: *16th annual International Technology, Education and Development Conference INTED 2022 Proceedings* (pp. 9908–9914). http://dx.doi.org/10.54941/ahfe1002503

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CHAPTER 1: INTRODUCTION

1.1 Background

Maritime pilotage (hereafter pilotage) is a critical aspect of the maritime industry, ensuring safe, efficient, and sustainable operations at sea. Pilotage is a safety-critical system (SCS) (Knight, 2002) with many of the seagoing vessels relying on maritime pilots (hereafter pilots) due to rigorous regulatory requirements and vetting processes designed to uphold navigational safety and ensure compliance with international maritime laws and standards (Hetherington et al., 2006; Sampson & Bloor, 2007). Pilots employ extensive local knowledge to provide navigational guidance to mariners in specific waterways. Pilots interact with the vessel's crew as indirect members of the team, offering advisory information on navigation and the specific characteristics of the waterway, such as depth, obstacles, tides, and infrastructure. They also assist in towing, berthing, and mooring operations (SMA, 2022).

Maritime pilot training (MPT) is a structured process designed to align pilot trainees (hereafter trainees) with the qualifications required of a pilot. The training consists of several phases, including classroom instruction, simulator exercises, and practical experience onboard vessels. Generally, pilots are experienced Masters with substantial seagoing experience. This prerequisite is crucial, as ship handling—along with knowledge of maritime laws and regulations, leadership, and communication skills (Sampson & Bloor, 2007; Eklund & Osvalder, 2022a/b)—are essential components of pilot operations.

A principal component of MPT is the apprenticeship, which can last from several months to around a year. During this period, trainees work under the supervision of senior pilots, learning the specifics of local waters, such as tides, currents, local infrastructure, and navigational hazards. This hands-on experience is essential for developing the skills necessary to navigate vessels safely along specific routes (Talley, 2009; Ziarati et al., 2009). Trainees typically enter the program as seasoned Masters with extensive experience in maritime operations, undergoing additional training to acquire the specialized skills required of pilots.

Another key component of modern MPT is simulator training. These simulators provide opportunities to practice navigating vessels under a wide range of conditions, such as varying weather, traffic, and both normal and non-normal scenarios, all within a controlled environment. This approach significantly reduces the risks associated with real-world operations and lowers training costs, allowing trainees to develop their skills in a safe and efficient manner (Barnett et al., 2003). Moreover, simulators are essential for familiarizing trainees with several types of vessels and for understanding the complex dynamics of ship behavior under various conditions (Barnett et al., 2002; Schröder-Hinrichs et al., 2012). Furthermore, simulator training enables trainees to practice their skills in interaction, communication, workload management, and decision-making in relation to other individuals on the ship's bridge, tugboats, or the Vessel Traffic Service (VTS) (Barnett et al., 2003; Chauvin et al, 2013).

1.2 Maritime Pilot Training

This licentiate thesis (hereafter thesis) is based on empirical studies conducted at the Swedish Maritime Administration (SMA), which provides pilotage within Swedish territorial waters, along with a Pilot Training Program (hereafter PTP). The PTP spans approximately one year and is divided into three parts. (1) Introductory Course (INTRO): Lasting 1–3 months, and covers employment conditions, safety regulations, SMA organization, and e.g., general pilotage procedures. (2) Basic Training for Maritime Pilot Course (hereafter BASIC): Lasting 6 weeks, and includes theoretical and practical components in ship handling (simulator training and practical ship handling in miniature vessels) related to maneuvering, controlled navigation, hydrodynamics, currents and wind, and tugboat operations. It also covers Marine Resource Management (hereafter MRM), duties of government officials, boarding operations, hoisting, and e.g., hypothermia management. (3) Local Training Plan Course (hereafter LTP): Lasting 6–12 months, and requires the trainee to participate in 50 to 150 actual pilot missions under supervision. The LTP concludes with an examination, after which the trainee becomes a certified pilot holding a Level 1 Guide note. The PTP includes classroom sessions, maritime simulator (hereafter simulators) training, and onboard vessel training. A recurrent course (hereafter RECUR) runs at fixed intervals following the PTP.

The transition from Master to pilot is a challenging process that requires high-quality didactic and pedagogical approaches (Eklund & Osvalder, 2022a/b). This transition can be understood as a form of partial re-skilling, where individuals acquire new competencies built on their existing skills, update current ones (Frey & Osborne, 2017), and shift into a new profession. In such a re-skilling process, knowledge transfer is crucial. Knowledge exists in various types, both formal and informal, with some types—such as tacit knowledge—more difficult to identify, capture, document, articulate, and transfer. Therefore, it is essential to continuously evaluate and improve the MPT to optimize knowledge management.

1.3 Aim and Research Questions

This thesis aims (1) to evaluate tacit knowledge transfer within SCS, with a particular focus on MPT and the PTP conducted in simulators; (2) evaluate the usability of eye-tracking as a didactic tool for identifying, documenting, and transferring tacit knowledge in the PTP; (3) examine tacit knowledge concerning its nature, transfer, and epistemology to enhance MPT didactically; and (4) propose guidelines for improving the MPT in terms of knowledge transfer.

- **RQ1** (Paper 1): How can the nature and transfer of tacit knowledge be interpreted within the framework of SCS?
- **RQ2** (Paper 2): What strategies are employed for the transfer of tacit knowledge in the PTP?
- **RQ3** (Paper 3): How can eye-tracking be utilized as a didactical tool for detecting tacit knowledge and improving its transfer during the PTP in simulators?
- **RQ4** (Chapter 5): How can tacit knowledge be defined and mapped in relation to other types of knowledge that exhibit overlapping characteristics or are used interchangeably?
- **RQ5** (Chapter 6): How can guidelines be formulated to enhance the PTP in terms of tacit knowledge transfer?

1.4 Organization of the Thesis

Chapter 1 introduces the topics of pilotage and MPT. Chapter 2 establishes the theoretical framework, while Chapter 3 outlines the methodological framework. Chapter 4 presents the findings of the empirical studies, and Chapter 5 examines tacit knowledge, focusing on its nature, transfer, and epistemology. Chapter 6 provides guidelines to enhance tacit knowledge transfer within the PTP. Chapter 7 discusses the findings in relation to the thesis aims, and Chapter 8 concludes by summarizing the thesis and its key outcomes. Additionally, Papers 1–3 are appended to provide further insights into the empirical studies.

2: THEORETICAL FRAMEWORK

This chapter presents an overview of the theoretical framework for the thesis, which covers socio-technical systems (STS), SCS, the integration of humans, technology, and organizations, knowledge, knowledge transfer, tacit knowledge, simulators, eye-tracking, and activity theory.

2.1 Socio-Technical Systems

In STS, technology and human actors are interdependent, each influencing the design, operation, and outcomes of the other (Baxter & Sommerville, 2011). The principle of joint optimization underlies the STS framework, asserting that both social and technical systems must be evaluated, designed, and managed in coordination to enhance overall system performance (Bostrom & Heinen, 1977; Pasmore, 1988). Thus, balancing technical requirements with human factors is fundamental to achieving successful outcomes (Kraut et al., 1990). This perspective challenges traditional approaches that focus solely on technical aspects, supporting a broader view that incorporates the needs, behaviors, and capabilities of users (Cherns, 1976) including experts as well as novices (Eklund & Osvalder, 2021).

Research on STS has been conducted across various domains, including healthcare, manufacturing, transportation, and information systems (Carayon, 2016; Graham et al., 2020), aiming to optimize the interaction between individuals, groups, and technology (Trist & Bamforth, 1951). This research emphasizes that organizational effectiveness depends not only on technical efficiency but also on the social interactions inherent in work processes (Emery & Trist, 1960a/b; Stranks, 2007). Furthermore, in the context of digitalization, socio-technical research has been employed to evaluate the challenges associated with technological change and innovation (Leonardi, 2011). It provides a framework for evaluating how new technologies impact organizational structures, work processes, and employee roles (Norris & Mrozek, 2016).

2.2. Safety-Critical Systems

Complex systems comprising automation, digitalization, and computerized interfaces (Moulton & Forrest, 2005) have been implemented across various industry domains to achieve safe, economical, and environmentally sustainable operations (Acharyulu & Seetharamaiah, 2015). Such systems share inherent complexity and carry the potential for severe consequences in the event of malfunction or failure (Rausand, 2014). When a malfunction or failure results in unacceptable outcomes, such as loss of life, significant property or financial damage, or environmental harm (Knight, 2002; Moulton & Forrest, 2005), the system is classified as an SCS system (Knight, 2002). However, these systems are designed to be highly reliable (Maurya & Kumar, 2020) and to prevent malfunction or failure during operation (Storey, 1996).

Examples of SCS can be found in various industries, including aerospace, medical, and telecommunications (Boy & Barnard, 2006; Acharyulu & Seetharamaiah), as well as in maritime and offshore operations (Eklund & Osvalder, 2022a/b), including pilotage (Crouch et al., 2013), nuclear power production (Engström, 2014), and the process industry (Osvalder & Colmsjö, 2017). As these systems continue to evolve, an increasing number of systems based on information and communication technology (ICT) are also becoming safety-critical, either directly or indirectly. This shift occurs due to their direct impact or because their failure or malfunction could lead to significant secondary consequences (Knight, 2002; Eklund & Osvalder, 2022a/b).

Safety in SCS refers to the system's capacity to operate without causing unacceptable harm to people, property, or the environment (Leveson, 2011). Hazard analysis is essential for identifying and mitigating risks in SCS, while redundancy is a critical feature that ensures that even if one component fails, backup systems maintain functionality (Storey, 1996). Moreover, SCS are designed to be either fail-safe—where the system continues to operate with reduced functionality in the event of a failure—or fail-operational, where the system maintains continuous and reliable operation until a safe state is reached (Storey, 1996). Given their complexity and the potential for severe consequences, SCS must adhere to stringent standards of reliability, safety, and performance (Rausand, 2014; Maurya & Kumar, 2020). For instance, in the aerospace industry, they are designed to achieve a probability of less than 1 x 10^{-9} accidents per flight hour (FAA, 1988; Bowen, 2000).

2.3 Integrating Humans, Technology, and Organization

In SCS and STS environments, the interdependence between technology and humans becomes more evident due to the potential risks associated with system malfunctions or failures. Such systems are not solely dependent on technical robustness; they also rely on how well they are integrated into an organizational context. This context encompasses human interactions within the organization, training and learning, regulations, surveillance, and compliance with established requirements (Leveson, 2011).

Research on the relationship between human, technology, and organization is therefore a key area of study within the broader field off SCS and STS. Such research aids in understanding how human factors, technological components, and organizational elements interact within these systems. This integration is crucial for optimizing, safety, system performance and user satisfaction (Emery & Trist, 1960a/b). The human component focuses on the users or operators within a system, including their needs, behaviors, skills, and interactions with technology (Hertzum, 2006). Understanding these aspects is essential for designing user-friendly, safe, and efficient systems (Norman, 2013). The technology component examines the tools, systems, and infrastructure involved, studying how these technologies are designed, implemented, and integrated into workflows (Shneiderman et al., 2016). The organizational component addresses the organizational context, encompassing structures, processes, culture, regulations, and policies (Checkland & Holwell, 1998).

2.4 Knowledge and Knowledge Transfer

Effective knowledge management is vital for organizations to improve performance (Nonaka & Takeuchi, 1995), remain competitive (Teece, 1998), ensure productivity (Haldin-Herrgard, 2000), and sustain safety-critical operations (Boy & Barnard, 2006). However, organizations face the risk of knowledge loss when experienced employees leave (Smith, 2001). To mitigate this, formal methods of assuring knowledge transfer—such as class-room lecturing, providing course literature, computer based training, mentoring, apprenticeships, and job rotation—have been developed alongside informal approaches like social networking, peer assistance, and casual interactions such as water-cooler or coffee-break discussions.

From a cognitive perspective, knowledge can be conceptualized as information that has been processed and internalized by an individual (Anderson, 1983). The relationship between data, information, knowledge, and wisdom—commonly referred to as the DIKW hierarchy—represents a continuum of understanding (Ackoff, 1989; Rowley, 2007). Data refers to raw facts that, in isolation, lack meaningful context (Rowley, 2007). When processed, data becomes information, contextualized to provide meaning (Baskerville & Dulipovici, 2006). Further refinement, integrated with experience, evolves into knowledge. Wisdom represents the final stage of this continuum, facilitating sound judgments and decisions, often incorporating ethical considerations and long-term perspectives (Schwartz and Sharpe, 2015).

Various frameworks also differentiate between explicit, implicit, and tacit knowledge. Explicit knowledge is easily articulated and can be conveyed through various mediums, including literature, instructions, and manuals (Nonaka & Takeuchi, 1995). Implicit knowledge refers to knowledge that has not yet been articulated, encompassing ideas, strategies, rules-of-thumb, or processes that remain undocumented but can potentially be articulated (Nickols, 2000; Howard et al., 2009). Tacit knowledge, on the other hand, includes knowledge that is challenging or impossible to articulate, often involving the execution of complex tasks developed through extensive experience (Polanyi, 1966; Leonard & Sensiper, 1998). Distinguishing between these types of knowledge prevents oversimplification and provides a clearer understanding of their roles within organizational contexts (Hedlund, 1994; Davenport & Prusak, 1998).

Knowledge transfer is a multifaceted process involving the sharing, dissemination, integration, and application of knowledge. It plays a crucial role in enhancing both individual and organizational performance (Teece, 1998), fosters innovation (Haldin-Herrgard, 2000), and enables organizations to learn from past experiences and implement best practices (Boy & Barnard, 2006). Furthermore, it ensures continuity, particularly in contexts where expertise is critical (Nonaka & Takeuchi, 1995; Argote & Ingram, 2000), such as in SCS and STS.

The SECI model (Nonaka & Takeuchi, 1995) conceptualizes knowledge creation as a continuous process involving four modes: (S) Socialization (tacit to tacit), where knowledge is transferred in a non-codified form; (E) Externalization (tacit to explicit), where knowledge is expressed or represented in an explicit form; (C) Combination (explicit to explicit), where knowledge is integrated; and (I) Internalization (explicit to tacit), where knowledge is absorbed and internalized. However, the SECI model has been critiqued for its level of abstraction and lack of empirical grounding (Glisby & Holden, 2003; Gourlay, 2006).

Formal training programs, including classroom instruction, computer-based training, and course literature, are structured initiatives designed to share explicit knowledge and develop skills. While initiatives such as social networking, peer assistance, and casual interactions—like coffee-break discussions (Lave & Wenger, 1991)—are more informal, mentoring and coaching allow experienced individuals to guide less experienced colleagues, thereby facilitating knowledge transfer also through observation and practice (Smith, 2001). Theories such as communities of practice (Wenger, 1998), constructivist learning (Piaget 1970; Vygotsky 1978), and the knowledge-based view (Grant, 1996) emphasize the critical role of social interaction in knowledge transfer and subsequent learning.

2.5 Tacit Knowledge

Tacit knowledge plays a central role in knowledge management, and its effective management is essential for several reasons. First, because it is deeply embedded in individual experience, tacit knowledge is crucial for the development of expertise and skills (Nelson & Winter, 1982). This type of knowledge is personal, context-specific, and inherently difficult to codify, formalize, articulate, or communicate (Polanyi, 1966). It evolves over time through practice and interaction, often in social settings (Nonaka & Takeuchi, 1995), and can manifest as practical skills (Nelson & Winter, 1982), know-how (Kogut & Zander, 1992), or muscle memory (Schmidt & Lee, 2005). Furthermore, it embodies the intuitive, experience-based understanding that individuals apply in various activities (Polanyi, 1966).

Although tacit knowledge is not easily articulated, it can still be transferred through social interactions; however, this does not always result in useful learning outcomes (Nickols, 2000). What may be tacit for one individual could, however, also be explicit for another (Dalkir, 2005). Spender (1993) and Ambrosini and Bowman (2001) further contend that tacit knowledge is inherently underspecified and resists formal operationalization. Consequently, research into tacit knowledge often necessitates a mixed-methods approach to adequately address its complexity. Additionally, tacit knowledge not only manifests in various appearances but also remains poorly defined in literature (Ambrosini & Bowman, 2001).

Tacit knowledge contributes to an organization by strengthening innovation, problem-solving, and decision-making capabilities (Nonaka & Takeuchi, 1995; Teece, 1998). Additionally, it ensures productivity (Haldin-Herrgard, 2000), promotes collaborative performance (Kogut & Zander, 1992), and, in SCS, its successful transfer is essential for maintaining operational safety (Boy & Barnard, 2006). Furthermore, effective tacit knowledge transfer ensures continuity in organizational processes, particularly when experienced employees leave, thereby preventing the loss of valuable expertise (Haldin-Herrgard, 2000).

Tacit knowledge is a crucial yet often ambiguous and misunderstood aspect of human cognition, learning, and expertise. This ambiguity stems from its varied interpretations, synonyms, and definitions, which typically encompass concepts such as skills, pattern recognition, reflexes, intuition, muscle memory, and competence. Tacit knowledge spans a wide range of domains (Collins, 2010) and faculties, including academic, operational, didactical, and cultural contexts. Distinguishing tacit knowledge from related cognitive processes—such as pattern recognition and intuition—can be challenging, as these concepts are interrelated and frequently overlap in practice. These distinctions are particularly relevant when investigating cognitive processes, learning mechanisms, and the development of expertise (Kogut & Zander, 1992).

2.6 Maritime Simulators

Maritime training has traditionally been conducted through apprenticeships, where novices transition into the profession by becoming socialized into the maritime culture (Hutchins, 1990). Over time, however, the development of nautical skills has shifted from traditional apprenticeship models to more formalized education and structured learning environments (Emad & Roth, 2008). A central feature of this evolution is the use of simulators, which reduce the time needed to spend onboard vessels (Bărsan, 2009), allow for the practice of potentially hazardous tasks in a safe and controlled environment (Nazir et al., 2015b; Passosa et al., 2016), thereby contributing to enhanced maritime safety (Hontvedt & Arnseth, 2013). Simulators develop both technical and non-technical skills (Baldauf et al., 2012) and facilitate the training and evaluation of work practices (Eklund & Osvalder, 2022a/b).

Simulators are utilized across various maritime domains, including offshore and oil rig operations training for both routine and emergency scenarios (Sellberg, 2017), nautical studies (Kim et al., 2021), and MPT (Eklund & Osvalder, 2022a/b). They are also employed in ship handling exercises, which involve controlled navigation, hydrodynamics, maneuvering, and interaction with ship bridge crews, tugboats, and VTS. However, the use of simulators does not automatically guarantee effective learning. The interaction between instructors and trainees is crucial (Hontvedt & Arnseth, 2013), as is the presence of a well-developed pedagogical and didactic framework to support the training process.

2.7 Eye-Tracking

Eye-tracking technology (hereafter eye-tracking) enables the evaluation of eye movements, including patterns, fixations, and durations, by estimating the point of gaze (Nivvedan, 2014). In maritime research, it has been utilized to evaluate activities on ship bridges, observe interaction, attention, vigilance, and situational awareness during training and evaluations (Muczyński et al., 2013; Hontvedt, 2015). In MPT, eye-tracking can support the observation of cognitive processes by analyzing gaze patterns to understand how pilots integrate and prioritize information. This allows researchers to infer the use of tacit knowledge, as well as explicit or implicit knowledge (Gegenfurtner et al., 2011). Eye-tracking further enhances visibility of the areas pilots focus on during task execution, facilitating the identification of strategies that might not be easily articulated (Van Gog et al., 2005). However, gaze focus alone does not guarantee cognitive engagement with the target; the individual may simply be looking at it without evaluating it cognitively. Fixation duration can be an indicator of rational strategies (Cooke, 2006; Holmqvist et al., 2011), but it can also suggest target fixation, stress, or contemplation of other tasks. Similarly, the frequency of fixations may reflect persistence in task-solving (Nakayama et al., 2002), but it could also indicate uncertainty, stress, or the use of random strategies. Thus, while eye-tracking provides valuable insights, it must be interpreted to distinguish between different cognitive and emotional conditions.

2.8 Activity Theory

Activity theory (Leontiev, 1978; Vygotsky, 1978) is a socio-cultural framework that examines human activity as socially mediated and goal-oriented, shaped by tools, community norms, and the division of labor (Engeström, 1987). It emphasizes collective learning through practical engagement and interaction with cultural and social tools, such as language, within social contexts (Vygotsky, 1978; Kaptelinin & Uden, 2013). Activity systems analysis is used to extract and analyze data related to social activities (Yamagata-Lynch, 2010) and has been applied in fields such as learning, design, and human-computer interaction (Kaptelinin & Nardi, 2006). An activity system consists of six components: the object (activity), the subject (individuals), the tool (mediating devices), rules (guiding activity), the community (social group), and the division of labor (work distribution). Tensions within these systems drive development and learning (Engeström, 2001). While activity theory has been applied in organizational studies, it remains underutilized or seen as overly specialized (Thompson, 2004). Nardi (1996) further described it as an analytical tool rather than a predictive theory, though Blackler and Reagan (2009) argue that its relevance lies in addressing dynamic relationships within organizations.

CHAPTER 3: RESEARCH DESIGN AND METHODOLOGY

This chapter offers an overview of the research design and methodology adopted in this thesis. It outlines the methodologies used to address the research questions, explains the rationale for selecting these methods, and details the processes involved in data collection and analysis.

3.1 Introduction

The author of this thesis holds significant expertise in two fields. First, in the academic sphere, with a Master in Psychology and a Master in Ergonomics & Human-Technology-Organization. Second, the author has extensive practical experience in both SCS and STS, having served as both an airline pilot, flight instructor in simulators, and a naval officer for over three decades. Key areas of convergence between these domains include topics such as safety, risk assessment, judgment and decision-making, stress and workload management, leadership and followership, communication, feedback, knowledge management, interpersonal dynamics, and didactics. The integration of studies in human behavior and human factors at both individual and group levels, combined with substantial practical experience, provides a foundation for understanding the interaction between theory and practice.

The research design selected for this thesis was a mixed-methods explanatory/exploratory sequential design, which is well-suited for obtaining diverse perspectives by allowing for both qualitative and quantitative data collection, thereby increasing the validity of the research (Creswell & Plano Clark, 2017). By integrating qualitative and quantitative data, the study aims to develop a deeper understanding of the phenomena under investigation, enhancing the interpretation and explanation of statistical results with greater nuance and depth (Ivankova et al., 2006). Additionally, this design improves the contextualization of measures by incorporating the subjective perspectives of participants, providing a more robust framework for understanding complex variables in their real-world context (Teddlie & Tashakkori, 2009).

3.2 Procedure

The data collection procedure is illustrated in Figure 1. First, a systematic literature review was conducted to evaluate the nature of tacit knowledge transfer within SCS (RQ1, Paper 1). Next, a mixed-methods design was employed to evaluate tacit knowledge transfer processes in PTP, using activity theory as a framework (RQ2, Paper 2). Subsequently, a mixed-methods design was applied to evaluate eye-tracking as both a general and didactical tool for managing tacit knowledge transfer in the PTP, with a particular focus on simulators (RQ3, Paper 3). Additionally, an explanatory synthesis design was utilized to investigate the epistemological nature and transfer of tacit knowledge, integrating insights from Studies 1–3. This design aimed to refine the definition of tacit knowledge to further analyze the PTP (RQ4, Chapter 5). The thesis concludes with guidelines, synthesized from Studies 1–3 and Chapter 5, which aim to enhance tacit knowledge transfer within the simulator parts of the PTP (RQ5, Chapter 6). This is followed by the conclusion in Chapter 7 and the discussion in Chapter 8.

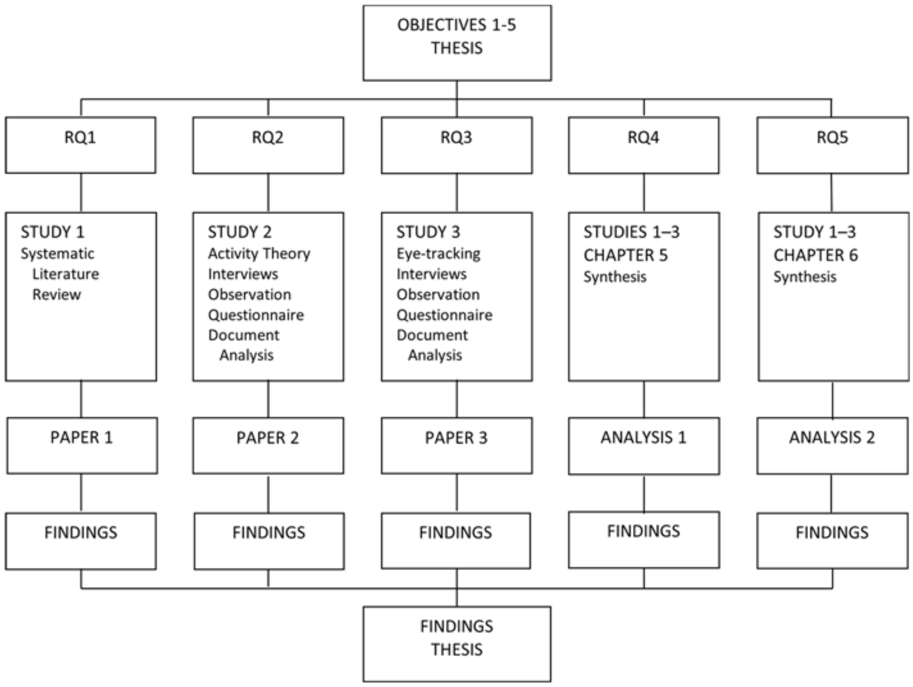

Figure 1. Compilation of the research procedure.

3.3 Mapping Tacit Knowledge Transfer in Safety-Critical Systems

Paper 1 (Study 1) involved a systematic literature review conducted using a seven-step design. The study aimed to explore and compile existing methodologies for transferring tacit knowledge within SCS. This process included defining the purpose and research questions, employing the SPIDER (Cooke et al., 2012) research strategy, applying the EPPI Centre (2007) inclusion criteria, performing literature searches, and conducting screening and selection in accordance with PRISMA guidelines (Page et al., 2020). Critical appraisal was carried out using the CASP (2018), MMAT (Hong et al., 2018), and AACODS (Tyndall, 2010) tools. The data were then synthesized using the SECI model (Nonaka et al., 2000), and the results were presented accordingly.

A total of 4,844 records were initially evaluated, comprising 4,732 sourced from databases and 112 from non-database sources. Titles and abstracts were randomly assigned, with the primary author reviewing 100% of the records and the secondary author reviewing a randomly selected 25% to mitigate bias and ensure redundancy. After applying reduction criteria—removing duplicates, ineligible records, incorrect domains, relevant domains but off-topic content, or substandard studies—22 empirical and non-empirical studies from various sectors were systematically examined. These sectors included nuclear power production, offshore operations, aerospace, control rooms, maritime, and railway operations, all of which had an operational focus. The findings were subsequently evaluated, classified, and presented using the SECI model.

3.4 Activity Theory for Evaluating the Pilot Training Program

Paper 2 (Study 2) employed a mixed-methods design grounded in activity theory to evaluate the PTP in terms of knowledge transfer. An eight-step model was used to conceptualize data from the PTP based on the activity system model (Engeström; 1987, 2001). The PTP was evaluated based on the elements of objects, subjects, tools, rules, community, division of labor, motives, and outcomes. Data were collected through questionnaires, semi-structured interviews, observations, and document analysis during two consecutive PTPs.

A total of 21 trainees and instructors participated in the study. The mean age of the participants was 46 years, with a standard deviation of eight years. All participants were experienced mariners who had previously worked as Masters on merchant vessels. All participants were males and had operated at seven different pilot stations in Sweden, each varying in terms of waters, infrastructure, vessel categories, and traffic conditions.

A six-point Likert scale questionnaire, which included both background questions and items assessing perceived knowledge transfer in the PTP, was completed by the participants. An even scale was chosen to eliminate a neutral center option (Allen & Seaman, 2007). Participants also engaged in semi-structured individual interviews that focused on their perceptions of knowledge transfer in the PTP. All interviews were recorded, transcribed, and analyzed using thematic inductive analysis (Clarke & Brown, 2006). Additionally, passive participant observations (Musante & DeWalt, 2010) were conducted in classrooms, simulators, pilot stations, and during actual pilotage. Field notes (Bogdan & Biklen, 2003) were collected and documented according to an observation protocol. The emerging data were thematized and analyzed using Mwanza's (2002b) eight-step model for interpreting an activity system.

A document analysis (Bowen, 2009), adapted from Rapley (2007) and Krippendorff (2004), was conducted to examine training curricula, course literature, operating procedure descriptions, intranet databases, printed and electronic documents, illustrations, and films. All documents were systematically reviewed and screened for the terms tacit, implicit, and skills, along with related terminology or meaning. Thematic inductive analysis (Clarke and Brown, 2006) was then applied to code and organize the data into themes.

3.5 Deploying Eye-Tracking in Simulator-Based Maritime Pilot Training

Paper 3 (Study 3) employed a mixed-methods design to evaluate the use of eye-tracking in simulators within the PTP. The study comprised four sub-studies conducted at various stages of the PTP. Data were collected through questionnaires, semi-structured interviews, observations, eye-tracking during simulator sessions, and document analysis over time.

A total of 57 participants—including pilots, instructors, and trainees—took part in the study. The mean age of the participants was 47 years, with a standard deviation of eight years. All participants were seasoned mariners who had previously served as Masters on merchant vessels.

A five-variable questionnaire, utilizing both five-point and four-point scales, was employed to gather subjective evaluations from participants following their use of eye-tracking. Semi-structured interviews (Edwards & Holland, 2013), guided by a predefined interview framework, aimed to collect more detailed insights into the usability of eye-tracking. These interviews were recorded via video and audio, transcribed, and analyzed using thematic inductive analysis (Clarke & Brown, 2006), with the data coded and organized into themes. Passive participant observations (Musante & DeWalt, 2010) were conducted during simulator training sessions, which included activities in simulators, classrooms, and briefing sessions. Field notes (Bogdan & Biklen, 2003) were collected according to an observation protocol. A document analysis (Bowen, 2009), adapted from Rapley (2007) and Krippendorff (2004), was conducted to examine training curricula, course literature, operating procedure descriptions, intranet databases, printed and electronic documents, illustrations, and films. All documents were systematically reviewed and screened for the terms tacit, implicit, and skills, along with related terminology. Thematic inductive analysis (Clarke & Brown, 2006) was then applied to code and organize the data into themes.

3.6 Evaluating Tacit Knowledge from an Epistemological Point of View

Analysis 1 (Chapter 5) contextualizes tacit knowledge by examining key topics identified in Papers 1–3, aiming to define its characteristics and distinguish it from related concepts. To achieve this, the chapter draws on an explanatory compilation of works by Polanyi (1966), Dreyfus and Dreyfus (1986), Klein (1998), Hofstede (2001), and Goleman (1995), followed by a synthesis of their insights (Creswell, 2014; Patton, 2002). The chapter begins with a summary of the research methodologies employed and the challenges inherent in investigating tacit knowledge. It then analyzes key related concepts, exploring their interconnections with tacit knowledge and producing a taxonomy. Following this, a framework is developed to deepen the understanding of tacit knowledge, outlining the specific contexts, methodologies, and timing of knowledge transfer within the PTP. The chapter proceeds with a deconstruction of tacit knowledge and concludes by presenting a synthesized general definition of tacit knowledge based on the methodological framework (Section 5.3), the findings from Papers 1–3, and partially on methodologies for synthesizing mixed-method findings (Creswell, 2014; Patton, 2002).

3.7 Guidelines for Improving Tacit Knowledge Transfer in the Pilot Training Program

Analysis 2 (Chapter 6) draws upon the findings presented in Papers 1–3 and Chapter 5 to present basic guidelines synthesized to enhance the transfer of tacit knowledge within the PTP. Mixed-methods designs were employed to enrich the depth of the synthesis and to develop a coherent narrative based on identified patterns and themes (Creswell, 2014; Patton, 2002). These guidelines are organized into two sections: the first outlines strategies for improving the PTP from an organizational perspective, while the second offers guidance on enhancing the PTP through research methodologies.

CHAPTER 4: FINDINGS OF APPENDED PAPERS

This chapter provides a summary of the findings from Papers 1–3 in the thesis.

4.1 Findings Paper 1: Tacit Knowledge Transfer in Safety-Critical Systems
A systematic literature review, conducted in accordance with PRISMA guidelines, aimed at exploring and compiling existing methodologies for transferring tacit knowledge within SCS. To achieve this aim, the SECI model was used to organize the findings.

- **RQ1**: How can the nature and transfer of tacit knowledge be interpreted within the framework of SCS?

Knowledge Creation: Socialization (Tacit Knowledge to Tacit Knowledge)
Tacit knowledge is often transferred through shared social experiences, which typically rely on physical proximity and interaction. These experiences can be both formal and informal. Common formal methods include scheduled meetings, apprenticeship programs, cross-training, partnerships with educational institutions, vocational learning, communities of practice, observation, and peer learning. Informal methods may involve casual conversations during coffee breaks, social activities, or informal mentoring. Social interactions foster shared values and build trust. In industries such as offshore operations and nuclear power plants, managing contract workers regarding their numbers and timing is common practice. Strategies for knowledge retention often include hiring individuals with long-term potential, developing knowledge retention plans for retirees, engaging retirees as consultants or instructors, and recruiting locally.

Knowledge Creation: Externalization (Tacit Knowledge to Explicit Knowledge)
Articulating tacit knowledge, thereby making it explicit and more easily shareable with others, is challenging. However, this process is crucial for transforming personal, experiential knowledge embedded within individuals into a format that can be documented and communicated across the organization. Common techniques used in this transformation include metaphors and analogies, which help convey complex ideas in more relatable terms. Storytelling is another effective tool, as it contextualizes knowledge within real-life scenarios, making it easier to understand and apply. Additionally, exit interviews capture valuable insights from departing employees, ensuring that their expertise is not lost. Brainstorming sessions and debriefings foster collaborative knowledge sharing by encouraging group reflection and discussion. Finally, the creation of databases or repositories facilitates the systematic collection and organization of explicit knowledge, ensuring it remains accessible for future reference and use by others in the organization.

Knowledge Creation: Combination (Explicit Knowledge to Explicit Knowledge)
Knowledge, both from within and outside the organization, is combined, converted, and synthesized into more complex and systematic sets of explicit knowledge. This process often involves integrating discrete pieces of explicit knowledge to form a cohesive whole. However, while combination enhances the organization of existing knowledge, it does not necessarily extend the knowledge base itself; rather, it augments and refines it. Common examples of combination include databases, wikis, guidelines, models, mock-ups, and manuals, which are often housed on digital platforms or portals. These tools serve as repositories of structured knowledge, enabling easy access and reference. In terms of information and communication technology (ICT), novice employees tend to rely more heavily on these formal systems and established company procedures for guidance. In contrast, more experienced personnel often adopt less formal and more proactive methods of transferring and sharing knowledge, drawing

on their familiarity with both tacit and explicit knowledge to navigate complex tasks and situations.

Knowledge Creation: Internalization (Explicit Knowledge to Tacit Knowledge)
Explicit knowledge is continuously evaluated, reflected upon, and eventually internalized by individuals. This process is essential for transforming explicit knowledge into tacit understanding, allowing it to become ingrained in personal expertise and decision-making. Examples of methods used for this purpose include golden rules, best practices, training in simulators, classroom lectures, and the use of collaboration software. Although best practices are often articulated and disseminated through explicit channels, their transfer is influenced by non-articulated, tacit elements. These elements are embedded in the individual expertise of employees and within the routines and culture of the organization. Thus, even though best practices may be communicated through structured and formal means, their successful adoption often depends on the nuanced, informal ways in which knowledge is applied and adapted to specific contexts.

4.2 Findings Paper 2: Tacit Knowledge Transfer in Maritime Pilot Training
A mixed-methods study was conducted with trainees participating in the PTP. Grounded partially in activity theory, the study employed observations, interviews, questionnaires, and document analyses to evaluate and describe the prevailing methods used for transferring tacit knowledge throughout the PTP.

- **RQ2**: What strategies are employed for the transfer of tacit knowledge in PTP?

Knowledge transfer
Trainees were exposed to knowledge in several ways, at various times, and across multiple locations, including pilot stations, pilot vessels, piloted vessels, scale ship-handling facilities, simulators, classrooms, and self-study sessions conducted either on-site or off-site. Informal interactions, such as those during meals, coffee breaks, walks, or leisure activities, also served as key nodes for knowledge transfer. These informal nodes were particularly significant for the transfer of potential tacit knowledge, often facilitated through storytelling, which helped to verbalize tacit knowledge to some extent. While instructors followed a set syllabus, this syllabus did not provide adequate didactic guidance on how the PTP should be implemented in terms of knowledge transfer.

Knowledge Transfer Instruments
Knowledge transfer tools primarily included the simulator, actual pilot missions during the LTP, and the creation of the navigation booklet. All three serve as important vehicles for transferring tacit knowledge. Trainees prepared for, performed, evaluated, and discussed simulator sessions in an open (non-punitive) environment, interacting with each other and with their instructors. This approach fostered a foundation for discussions and reflections on completed sessions, creating a collective learning environment.

Briefings and debriefing sessions exposed trainees to tacit knowledge through interactions with their instructors. This knowledge often took the form of heuristics, including golden rules, guidelines, practical experience, and know-how. Non-situated theoretical learning, such as ship handling, trim and stability, or hydrodynamics, is addressed in the PTP but is largely assumed to have been previously acquired and is trained to a higher standard. Since the trainees are already experts in their profession as mariners, the PTP can be seen as an extension of their existing expertise. However, comprehensive course literature, which could provide a structured and organized way to review prior knowledge and introduce new concepts, was lacking.

Learning in a Social Environment
In the LTP, trainees took on the role of apprentices, making progress toward their new profession within a community of practice that was embedded in real-world pilot missions. Through continuous interactions with their supervisors, trainees acquired trade-specific, hands-on knowledge essential for their development. The LTP provided ample exposure to tacit knowledge, which was partially crystallized in the navigational booklet, which plays a vital role in the learning process. The booklet serves a dual purpose: it acts as a didactic tool that helps consolidate and reinforce the knowledge acquired during the training, and it also functions as a personal knowledge base. This dual functionality supports trainees by providing a structured reference for future pilot missions, ensuring they have a readily accessible resource for ongoing learning and practice.

4.3 Findings of Paper 3: Eye-tracking and Tacit Knowledge in Maritime Pilot Training
A mixed-methods study was conducted involving trainees, pilots, and instructors in the PTP with the aim of evaluating eye-tracking both as a specific didactic tool to enhance the transfer of tacit knowledge and as a general didactic tool. The study employed observations, interviews, questionnaires, and document analyses. However, the scope of this thesis was limited to the first aim; consequently, the second aim was omitted from the thesis.

- **RQ3**: How can eye-tracking be utilized as a didactical tool for detecting tacit knowledge and improving its transfer during the PTP in simulators?

Knowledge Transfer in the Pilot Training Program
Trainees were exposed to knowledge in explicit, implicit, and tacit forms. Explicit knowledge was conveyed through educational materials, such as course literature, slide presentations, manuals, and structured descriptions of simulator training sessions. Implicit knowledge was typically conveyed through oral guidelines rather than written texts, often during pre-, mid-, or post-session briefings during simulator training. In these instances, instructors supplemented and enriched the formal course materials with additional thoughts, ideas, reflections on actions taken, and alternative approaches.

However, it remained uncertain whether tacit knowledge was actually transferred during the simulator portion of the PTP or if the training predominantly covered related topics such as intuition, procedural knowledge, pattern recognition, or e.g., muscle memory. Instincts, defined as innate inclinations toward particular behaviors, and reflexes, which are involuntary responses to stimuli (Fischer & Truog, 2015), lack learning elements. Intuition, often understood as unconscious or preconscious pattern recognition (Gigerenzer, 2008), may interact with muscle memory, where actions are repeated over time, leading to the acquisition of know-how. Muscle memory, as developed in the PTP, appears to be more aligned with general nautical skills, such as ship handling, rather than pilot-specific expertise. At observed potential tacit knowledge transfer point, trainees or instructors were generally able to articulate their actions using step-by-step protocols, thereby challenging the classification of these actions as tacit knowledge.

Eye-tracking and Tacit Knowledge
The study further showed that training in simulators primarily focused on ship handling, including controlled navigation, maneuvering, current and wind effects, hydrodynamics, and tugboat operations, with additional emphasis on cross-cultural and group dynamics during MRM training. While these skills are crucial, they are not exclusive to pilots; rather, they are generally applicable to all mariners. However, these skills were trained to a higher standard in the PTP, incorporating the pilot’s role as an adviser and an indirect crew member, as well as preparing the trainee for the upcoming LTP.

In a partial MRM training session involving both junior and senior pilots, senior pilots occasionally noticed subtle details or patterns that junior pilots missed. In this context, eye-tracking facilitated the identification of these subtle learning cues, enhancing the junior pilots' abilities to recognize and prioritize critical information.

While eye-tracking can capture and display events of interest in the PTP, it requires further research for effective analysis. Observing, analyzing, and interpreting these events proved challenging, as the processes connecting fixation, learning, and the formation of tacit knowledge remain unclear. Nevertheless, these events can serve as a foundation for reflective discussions and may indirectly facilitate the transfer of tacit knowledge or related concepts, such as pattern recognition. When deploying eye-tracking during a customized approach, performed by an experienced pilot, to a harbor including challenging costal navigation a video-recording based on eye-tracking was created. Such a video, displaying both the interior and outside view of the ship's bridge, along with eye fixation data and step-by-step comments on actions, could serve as a foundation for developing a potential Standard Operating Procedure (SOP) for that particular passage. However, because it lacks consideration of cross-cultural and group dynamics, this SOP, based on eye tracking, may not still adequately capture the nuances of tacit knowledge and its transfer.

CHAPTER 5: MAPPING AND DECONSTRUCTING TACIT KNOWLEDGE

The aim of this chapter is to evaluate the nature of tacit knowledge from an epistemological perspective. Drawing on the studies presented in Papers 1–3, this chapter employs an explanatory synthesis design (Patton, 2002; Creswell, 2014) to achieve this aim. It begins with (1) a summary of the research methodologies employed, discussing the challenges associated with investigating tacit knowledge. Following this, (2) an analysis of key related concepts is provided, exploring their interrelationships with tacit knowledge and the PTP, which culminates in the development of (3) a taxonomy. Subsequently, (4) a framework is developed to enhance the understanding of tacit knowledge. The chapter concludes with (5) a deconstruction of tacit knowledge itself, resulting in (6) a general definition grounded in the methodological framework, which is then compared to the PTP. Finally, the findings from this chapter are (7) translated into guidelines presented in Chapter 6, aimed at enhancing the understanding of tacit knowledge transfer in the PTP.

5.1 Articulating the Inarticulable: Tacit Knowledge Research Methodologies in Practice

Fundamental challenges in researching tacit knowledge primarily lie in its definition and operationalization. First, tacit knowledge exists across various faculties, including scholarly, operational, didactical, and cultural settings (Collins, 2010). Differentiating tacit knowledge from closely related concepts, such as pattern recognition, intuition, skill, and procedural knowledge, can be challenging, as these elements are often interrelated and overlap in practice. Such distinctions are crucial when investigating cognitive processes, learning mechanisms, and the development of expertise (Kogut & Zander, 1992).

Secondly, research instruments often require individuals to articulate aspects of their knowledge that may be inherently difficult or even impossible to fully express (Polanyi, 1966). Consequently, this resistance to articulation presents challenges for the operationalization of tacit knowledge. Nonetheless, these instruments can still be valuable for data collection (Carmines & Zeller, 1979). A variety of research methodologies are thus employed to study tacit knowledge, with ethnography, case studies, interviews, and observations being particularly prominent. These methodologies interact and complement each other, allowing for the distinction between what may constitute tacit knowledge and what may not, while also capturing more subtle aspects of knowledge (Nonaka & Takeuchi, 1995). Ethnographic approaches allow for in-depth cultural and contextual analysis, while case studies provide detailed insights into specific organizational settings (Yin, 2018). Furthermore, interviews and observations facilitate the collection of grounded data by enabling direct engagement with individuals' experiences and practices (Kvale & Brinkmann, 2009).

In addition to qualitative designs, experimental setups, neurocognitive methodologies, and simulations have also been recognized as suitable for exploring the tacit dimensions of knowledge. Therefore, employing a mixed-methods research design allows for the examination of the topic from both qualitative and quantitative perspectives, thereby providing an improved understanding (Denzin, 1978; Creswell & Plano Clark, 2017) and promoting triangulation, complementarity, and validation of findings across multiple data sources (Flick, 2018).

The integration of machine learning has shown potential in modeling and analyzing complex patterns in data that reflect implicit knowledge (Davenport & Ronanki, 2018). Additionally, the use of neurocognitive methodologies, such as functional magnetic resonance imaging (fMRI) and electroencephalography (EEG), allows researchers to compare brain activity during the execution of automatic motor skills, which rely on muscle memory, with tasks involving evaluations and decision-making that may be linked to tacit knowledge (Gazzaniga et al., 2018). This research generates neural patterns during task completion, which can be mapped, categorized, and associated with their respective cognitive processes (Schmidt & Lee, 2005).

To differentiate between learned behaviors based on tacit knowledge and innate responses, such as instincts or reflexes (Chartrand & Bargh, 1999; Dweck, 2006), longitudinal studies can be useful as they track the development of skills over time (Schaie, 1965; Ericsson & Charness, 1994) and compare them with innate mechanisms, like instincts, which do not significantly change with the acquisition of expertise. Conducting cross-cultural comparisons is another method for evaluating tacit knowledge, as it can vary significantly depending on cultural contexts (Polanyi, 1966; Hofstede, 2001). This approach examines how cultural values and practices influence the development and application of tacit knowledge (Triandis, 1995; Schwartz, 1999).

5.2 Contrasting Tacit Knowledge: Mapping the Epistemological Landscape

Sections 5.2.1–5.2.11, along with Table 1, contextualize tacit knowledge in relation to the most common and closely related topics discussed in Papers 1–3. A comparative explanatory compilation, based on the works of Polanyi (1966), Dreyfus and Dreyfus (1986), Klein (1998), Hofstede (2001), and Goleman (1995), has been developed to explore tacit knowledge in relation to other relevant concepts. These concepts include implicit knowledge, procedural knowledge, skills, know-how, muscle memory, intuition, reflexes, instinct, cultural norms, social learning, and pattern recognition. Furthermore, each section examines the contexts and methodologies associated with the transfer of knowledge and compares them to the PTP.

5.2.1 Implicit Knowledge

Implicit knowledge is knowledge that is not explicitly expressed or documented but is nevertheless understood and applied in practice. This type of knowledge may include thoughts or ideas that have not yet been articulated (Polanyi, 1966; Nonaka & Takeuchi, 1995) or documented and communicated. While implicit knowledge can be a subset of tacit knowledge and is often used interchangeably, it also encompasses knowledge that individuals are aware of but have not formalized into explicit forms (Eisenhardt & Martin, 2000). Like tacit knowledge, implicit knowledge is personal and experience-based, but it is less deeply rooted.

In the PTP, implicit knowledge encompassed information that was not explicitly articulated in written form but was conveyed verbally or through combinations of e.g., video and animations from training sessions in the simulator. Instructors shared this knowledge as a complement to explicit knowledge, reinforcing the learning experience by addressing gaps where the amount of explicit knowledge could be improved or were lacking. This information was often illustrated directly on a whiteboard with animated overlays from the simulator sessions, thereby facilitating meta-learning and enriching the knowledge transfer process.

5.2.2 Procedural Knowledge

Procedural knowledge refers to the understanding of how to perform tasks, procedures, or operations (Anderson, 1983). Procedural knowledge can be broken down into systematic steps and methods, which can be articulated, and documented making it easier to communicate and teach (Schön, 1983). Although procedural and tacit knowledge are related, they differ. While procedural knowledge is often implicit, it can be made explicit through demonstrations, verbalizations, or by translating it into written instructions (Anderson, 1983).

Procedural knowledge can be mistaken for tacit knowledge, particularly when the execution of a task appears automatic or effortless. Identifying gaps between an individual's actions and their descriptions, using techniques such as think-aloud protocols, allows exploring the cognitive processes underlying these actions (Ericsson & Simon, 1980). This approach helps to distinguish procedural knowledge from tacit knowledge during task performance.

In the PTP, observing instructors and trainees performing maneuvers in simulators sometimes revealed an effortless, almost automated application of skills. However, when asked to describe their actions using think-aloud protocols, they were able to articulate and effectively communicate these maneuvers. When combined with videos from specific pilotage routes, these verbalizations proved valuable as didactic tools, especially when integrated with eye-tracking. This combination facilitated the development of SOPs, which could be presented in both written form and through videos.

5.2.3 Skills

Skills refer to the ability to perform a task or activity effectively, typically developed through practice, training, or experience (Anderson, 1982; Eraut, 2000). Often considered explicit knowledge, skills are measurable, can be demonstrated through performance, and can also be articulated using think-aloud protocols. They are acquired and honed through years of education and practice (Dreyfus & Dreyfus, 1980). Skills are taught formally and evaluated through performance-based evaluations, making them relatively easy to articulate, document, and transfer.

Tacit knowledge and skill are often interrelated concepts in the context of learning and expertise; however, they represent distinct aspects of human cognition and capability. Tacit knowledge is characterized by its implicit nature, often residing in the subconscious and being difficult to verbalize or formalize. It encompasses a holistic understanding and intuitive perception of situations. In contrast, skill refers to the learned ability to perform tasks or activities with proficiency, often developed through repetition and practice (Dreyfus & Dreyfus, 1986).

In the PTP, skills development was observed, for example, during the training of birthing maneuvers in the simulator where the trainee coordinated the operations of their own ship while also communicating with VTS and tugboats. Instructions provided to the tugboat officers included thrust values and directional guidance. These values were applied in a step-by-step manner, articulated clearly, and adjusted as necessary in accordance with the established birthing plans, which considered factors such as weather, visibility, and the effects of current and wind. Over time, these step-by-step instructions were assimilated and evolved into a developed skill.

5.2.4 Know-How

Know-how represents a deeper understanding of how to accomplish a task, often combining theoretical knowledge, practical skills, and experiential insight (Polanyi, 1966). It includes procedural elements but also requires an intuitive grasp of when and how to apply these procedures flexibly, particularly in novel or unpredictable situations (Schön, 1983). This capacity for adaptability is what links know-how closely with problem-solving and the flexible application of skills, requiring an understanding of processes and methods (Eraut, 2000). As a result, the transfer of know-how is challenging, often necessitating situated learning experiences such as apprenticeships or mentoring (Brown & Duguid, 1991).

Know-how shares characteristics with tacit knowledge. Tacit knowledge is developed through personal experience and is often difficult to articulate (Polanyi, 1966). Know-how, similarly, often involves an implicit dimension, but it is typically more transferable, as it can be communicated to some extent through demonstration, observation, and hands-on learning.

In the PTP, ship handling constitutes only one aspect of pilot-specific know-how, yet it was trained to a higher level. While the foundational development of pilot-specific know-how was initiated in the simulators, the majority of this development is expected to occur in the LTP, where apprenticeships provide a more authentic learning environment. Furthermore, the lack of interaction with real ship bridge crews and actual vessels hindered the development of know-how to some extent during the simulator part of the PTP.

5.2.5 Muscle Memory

Muscle memory refers to the process by which physical tasks become nearly automatic through repetition. It is specifically related to physical tasks and can be viewed as a subset of procedural knowledge (Lamm & Madsen, 2015). This form of knowledge enables the body to perform tasks with minimal conscious effort (Schneider & Shiffrin, 1977). The process involves encoding motor tasks through repeated practice, embedding specific movements within the nervous system (Willingham, 2004; Schmidt & Lee, 2005). Muscle memory functions through procedural memory, allowing individuals to execute these tasks with little conscious thought after extensive practice (Squire, 2004).

Muscle memory can be considered a subset of tacit knowledge, particularly in terms of physical tasks, where it manifests as actions that seem automatic but are not innate (Squire & Zola-Morgan, 1991). While muscle memory primarily relates to physical actions and skills linked to the motor system, tacit knowledge encompasses a broader spectrum, developed through varied experiences and interactions across diverse contexts over time. Although individuals can articulate certain aspects of muscle memory, the automatic and implicit nature of this phenomenon makes comprehensive articulation challenging.

In the PTP, muscle memory was a principal component of training, facilitating the acquisition of essential skills through repetitive practice and simulation exercises. By fostering automaticity in physical tasks, muscle memory enabled trainees to respond effectively in realistic scenarios, even under time constraints. The repeated performance of tasks in the simulator enhanced the development of muscle memory, which is necessary for executing complex maneuvers seamlessly during actual piloting. However, like other forms of knowledge, these skills were only trained to meet elevated standards, as the profession of piloting imposes distinct requirements on their abilities.

5.2.6 Intuition

Intuition refers to the ability to understand or know something instantly, without the need for conscious reasoning. Over time, vast amounts of data, information, knowledge, and experiences are stored in our cognitive systems, often without full awareness. Individuals can tap into these repositories as intuitions, accessing insights without conscious effort, which makes it challenging to articulate or rationalize these feelings (Kahneman, 2011). It is often described as a gut feeling or insight that allows individuals to reach conclusions rapidly (Kahneman, 2011; Gigerenzer, 2008). Moreover, intuition is linked to cognitive processes, particularly the ability to recognize patterns, cues, or structures based on previous experiences (Simon, 1992). In practical terms, intuition acts as a first line of judgment, influencing decision-making processes often without individuals being fully aware of it (Tversky & Kahneman, 1974; Betsch, 2008). This intuitive capacity tends to be more reliable among experts, who have had extensive exposure to specific phenomena, resulting in larger cognitive repositories that are more readily accessible compared to those of novices (Klein, 1998; Hogarth, 2001).

Tacit knowledge involves an intuitive understanding that develops with experience. While it may feel instinctive, it is grounded in various forms of knowledge, such as intuition, and experiences that have been internalized over time. However, tacit knowledge encompasses a broader range of insights and experiences, including, but not limited to, intuition. Thus, intuition is related to tacit knowledge, but it involves making rapid judgments without conscious reasoning to a greater extent (Polanyi, 1966; Hogarth, 2001). Although intuition is challenging to transfer directly, it can be articulated indirectly through analogies or metaphors, whereas tacit knowledge is even more difficult to express.

In the PTP, signs of intuition were observed during simulator sessions when participants expressed feelings or insights that were often difficult to articulate before executing a ship maneuver. During these sessions, the pilots utilized and communicated non-codified implicit knowledge in addition to explicit knowledge, which may not be captured in navigational charts. This implicit knowledge encompasses intuitive insights, described as gut feelings. While some aspects of this knowledge can be broken down into discrete elements—such as the effects of wind angles, turning points, turn rates, speeds, currents, or relative movements—other aspects, particularly the integration of various informational elements, may resist formal articulation and thus be categorized more as tacit knowledge.

5.2.7 Reflexes

A reflex is an involuntary, automatic, and nearly instantaneous movement in response to a specific stimulus, controlled directly by the nervous system without conscious thought or decision-making. Reflex actions serve protective or adaptive functions, such as the corneal reflex (Snell, 2012) or the startle reflex (Brazelton and Sparrow, 2006), helping individuals respond quickly to potential dangers or changes in their environment (Sherrington, 1906). Reflexes differ from instincts in that reflexes are simple, automatic responses to specific stimuli, while instincts are more complex behaviors involving patterns of actions (Lorenz, 1966).

Reflexes are automatic responses that occur without conscious deliberation, while tacit knowledge involves elements of learning and experience. Both reflexes and tacit knowledge share non-conscious properties (Polanyi, 1966; Reber, 1993). However, tacit knowledge evolves gradually and can lead to behaviors that resemble reflexive automaticity, particularly as individuals achieve expert proficiency in a skill (Dreyfus & Dreyfus, 1980; Logan, 1988). Over time, skills derived from tacit knowledge can take on a reflex-like quality, especially in highly practiced actions, where behaviors are executed with minimal conscious thought—much like reflexes, although they do not qualify as reflexes in the strictest sense (Logan, 1988). While reflexes are typically classified as physiological responses of the body, tacit knowledge represents a cognitive phenomenon.

In the PTP, simulator training provided trainees with opportunities to experience and mitigate reflexive responses, akin to defusing instinctive reactions and subsequent behaviors, all within a controlled environment. This training included scenarios that often simulated non-normal situations, which triggered reflexes such as the startle reflex. Through iterative practice in these scenarios, trainees learned to manage their reactions under pressure more effectively.

5.2.8 Instinct

An elementary characteristic of instinctual behaviors is their automatic nature, as they occur without conscious thought, judgment, or decision-making. Instincts differ from learned behaviors, which are acquired through experience, practice, or conditioning over time. Instincts are innate, natural responses shaped by evolutionary mechanisms to enhance survival (Bornstein et al., 2017; Hoehl et al., 2017) and self-preservation (Green et al., 2003), or to initiate fixed action patterns (Páez-Rondón, 2018). Unlike learned behaviors, instincts emerge without external instruction and manifest consistently across individuals in predictable situations (Gottlieb, 1998). While instincts themselves operate as automatic and largely non-conscious mechanisms, the associated feelings represent the conscious awareness and interpretation of the physiological and emotional responses triggered by the instinct.

While instinct is innate and biologically determined, tacit knowledge is cultivated through experience and social learning, evolving with practice and repeated exposure to relevant contexts (Eraut, 2000). Although tacit knowledge and instinct may appear similar in practice—both can lead to swift, seemingly automatic judgments or actions—their origins differ fundamentally. Instinct is fixed and innate, rooted in evolutionary biology, while tacit knowledge develops and adapts through practical engagement with the world (Nonaka & von Krogh, 2009). Additionally, instinct is rigid and unchanging, whereas tacit knowledge is flexible, adaptable, and shaped by ongoing experience (Leonard & Sensiper, 1998), making it especially valuable in situations that demand expertise and adaptability.

In the PTP, biological instincts were neither learned nor trained. However, a key aspect of the simulator training involved refining or mitigating instinctual responses in stressful situations, much like reflexes. For example, fight-or-flight reactions to perceived danger can be moderated through repeated exposure to simulated high-pressure scenarios. By practicing critical situations iteratively in the simulator, trainees can reduce the intensity of their instinctive responses, allowing them to manage their reactions more effectively in real-world events.

5.2.9 Cultural Norms

Cultural norms are shared expectations and rules that guide behavior within a community. These norms can be explicitly taught through formal education or implicitly learned through observation and interaction. They play a crucial role in shaping social interactions by establishing standards of conduct within the community (Hofstede, 1980). As external factors, cultural norms provide a behavioral framework (Schwartz, 1994) and includes a wide range of practices, including communication styles, procedures, and approaches to problem-solving and decision-making. Understanding these norms is vital for cross-cultural communication and interaction, as they can influence the behavior and performance within these communities (Hofstede, 2001).

While cultural norms and tacit knowledge differ—cultural norms being external and often explicitly taught, and tacit knowledge being internal and experiential—they are closely intertwined. Cultural norms shape the formation of tacit knowledge by providing a behavioral framework that influences individual experiences and learning processes (Trompenaars & Hampden-Turner, 1997). Conversely, tacit knowledge enables individuals to navigate, internalize, and reinforce these norms, allowing for intuitive responses to social situations that align with culturally accepted behaviors (Dreyfus & Dreyfus, 1980).

In the PTP, pilots acting as instructors and mentors pass down both technical knowledge and organizational culture to trainees. During simulator sessions, trainees are trained to collaborate effectively with the (acting) crew of the piloted ship, particularly in stressful scenarios such as birthing. One key aim of the PTP is to integrate trainees into the culture of the SMA and its subsequent pilot operations. While some aspects of this cultural assimilation are addressed during simulator training, it primarily serves as preparation for further development during the LTP. A core component of this preparation is MRM training, conducted in simulators replicating real pilot mission scenarios. Through MRM training, trainees learn to utilize all available resources to ensure safety, operational efficiency, and clear communication.

5.2.10 Social Learning

Social learning refers to the process of acquiring knowledge, behaviors, and skills through interactions within a social environment. It emphasizes learning by observing others, imitating their actions, receiving feedback, and engaging in shared activities (Bandura, 1977). This learning often occurs in collaborative settings where individuals share information, participate in joint activities, and observe how others navigate tasks or solve problems. Through these interactions, learners co-construct knowledge by drawing from both personal experiences and the behaviors of others, reinforcing the idea that learning is inherently social (Vygotsky, 1978).

While tacit knowledge and social learning are distinct concepts, they are closely interrelated. Social learning enables the acquirement of tacit knowledge through observing others' techniques, practices, and behaviors, as well as through imitation and hands-on practice (Nonaka & Takeuchi, 1995). The difference is the learning process: social learning is an interactive process, involving collaboration and engagement with others, while tacit knowledge is deeply personal, individualized, and accumulated through lived experiences over long periods of time. However, tacit knowledge can also be indirectly transferred through social learning, even though it may remain largely unarticulated (Schön, 1983).

In the PTP, observing social learning was challenging, as with other topics related to tacit knowledge, as much of the social interaction and the subsequent learning is expected to take place during the LTP rather than in the simulator sessions. The controlled and structured nature of simulator environments may limit the opportunities for social interactions, which are crucial for the informal and observational learning processes that typically characterize social learning. This suggests that the more experiential, interaction-based aspects of training are likely to develop outside the simulator, in real-world contexts where apprentices engage with seasoned pilots and real ship crews.

5.2.11 Pattern Recognition

Pattern recognition is a cognitive process that involves identifying regularities, cues, or structures within data or experiences. This process can occur both consciously and unconsciously and is essential for interpreting both familiar and novel environments (Neisser, 1967; Goldstone & Son, 2005). By enabling the recognition of similarities, trends, and recurring elements across various situations, pattern recognition plays a crucial role in cognitive functioning (Lamberts & Goldstone, 2005). The development of this capability occurs through exposure to repeated stimuli (Sakai, 2008). Pattern recognition can be cultivated through training, but it is also considered an inherent cognitive function (Thorndike, 1911).

Pattern recognition and tacit knowledge are closely related concepts that refer to various aspects of cognition. Pattern recognition plays a crucial role in developing tacit knowledge, as repeated encounters with similar situations enable individuals to identify patterns within those experiences (Dreyfus & Dreyfus, 1980). Over time, this ability to recognize patterns evolves into a form of tacit knowledge. However, differentiating tacit knowledge from pattern recognition can be challenging (Polanyi, 1966; Reber, 1993). While pattern recognition focuses on identifying and categorizing patterns within data and is typically more explicit and systematic, tacit knowledge encompasses a deeper understanding that informs intuitive judgments and actions based on accumulated experience (Kahneman, 2011). Moreover, pattern recognition is generally more observable and formalizable, whereas tacit knowledge is inherently subjective and difficult to articulate (Neisser, 1967).

In the PTP, the development of pattern recognition is an important aspect of training, as it enables trainees to quickly identify and respond to various situations that may arise during navigation and maneuvering. Trainees cultivate this ability through exposure to diverse scenarios in simulators that replicate real-world exercises. The use of simulators provides a controlled environment where trainees repeatedly encounter scenarios, allowing them to learn to recognize common patterns in different vessel behavior. Pilots who can swiftly identify familiar patterns are better equipped to anticipate potential problems and implement appropriate solutions. This capability is particularly vital in high-pressure situations where time is critical. However, the recognition of behavioral, cross-cultural, or group dynamics patterns could not be adequately trained during simulator sessions.

Table 1
A taxonomy on tacit knowledge in term of related concepts

Concept	Definition	Relation to tacit knowledge	Can be articulated	Reference
Tacit Knowledge	Knowledge that is difficult or impossible to articulate, deeply personal, and often acquired through experience, and is key in applying skills and expertise in real-world situations.	N/A	Not articulable, or articulable with difficulties.	Polanyi (1966) Nonaka (1995)
Implicit Knowledge	Knowledge that is not yet, deliberate or undeliberate, articulated but can be articulated and formalized.	Tacit knowledge is broader, experience-based understanding, difficult or impossible to articulate, while implicit knowledge can be articulated in actions, text or words.	Articulable, but has not yet been.	Sternberg & Horvath (1999)
Procedural Knowledge	Knowledge of how to perform specific tasks, often stored as sequences or actions. May or may not include expertise, de-pending on experience and skill level.	Procedural knowledge is influenced by tacit knowledge, as applying procedures often relies on it. It involves skills and routines developed through practice. Over time, procedural knowledge can evolve into tacit knowledge when tasks are per formed automatically, without consciously recalling the specific steps.	Articulable using e.g. step-by-step techniques or think-aloud protocols.	Anderson (1982) Dreyfus & Dreyfus (1986)
Skills	The ability to perform tasks with expertise, developed through repeated practice and experience. Practical and context-specific knowledge, often broader and experiential.	Skills have a significant tacit element, as expertise builds over time and with exposure. They are a core component of tacit knowledge, especially in complex environments. Skill development relies on multiple knowledge types, with tacit knowledge playing a key role in enhancing and refining skills.	Articulable using e.g. step-by-step techniques or think-aloud protocols.	Eraut (2000) Schön (1983)
Know-How	A deeper understanding of how to accomplish a task, combining practical knowledge and experience. Includes procedural knowledge	Know-how is influenced by tacit knowledge, serving as the foundation for practical abilities and skills. Tacit knowledge encompasses the experiential insights that in form how to apply know-how effectively in various contexts	Articulable using e.g. step-by-step techniques or think-aloud protocols.	Ryle (1949) Nonaka (1995)
Muscle Memory	The unconscious, automatic execution of physical tasks after repeated practice, influenced by procedural and tacit knowledge.	Muscle memory is a form of procedural knowledge that becomes tacit as it no longer requires conscious thought during performance. It reflects the internalization of skills through repeated practice, making actions automatic and intuitive.	Not articulable, operates at an unconscious level, making it difficult to articulate.	Anderson (1982) Wolpert et al. (2011)
Intuition	Immediate understanding or decision-making without conscious reasoning, often based on pattern recognition from learning and experience	Intuition is often rooted in tacit knowledge, formed by experience. Tacit knowledge enhances intuitive decision-making by providing a deeper understanding of con textual cues, allowing for quicker and more informed judgments.	Not articulable, emotional or physiological manifestations can be articulated, not the mechanisms behind.	Gigerenzer (2008) Kahneman (2011)
Reflexes	Innate, automatic, specific, immediate, and involuntary physical responses to stimuli mediated by the nervous system, without conscious thought or learning.	While reflexes are distinct from learned knowledge types like tacit knowledge, individuals can learn to moderate their reflexive responses through experiences based on tacit knowledge, enabling more adaptive behavior in various situations.	Not articulable, operates at an unconscious level, making it difficult to articulate.	Fischer & Truog (2015)
Instincts	Innate, automatic, include broader patterns of behavior includes complex sequences of actions. Not acquired through learning, functions without conscious thought.	Instincts contrast with tacit knowledge, as they are innate rather than learned. However, tacit knowledge can influence instinctual responses, refining reactions based on prior experiences and learned behaviors.	Not articulable, emotional or physiological manifestations can be articulated, not the mechanisms behind.	Tinbergen (1951) Pinker (1997)
Cultural Norms	Shared behaviors, values, and beliefs that shape actions and decisions within a group or society, influenced by contextual factors.	Cultural norms influence how tacit knowledge is formed and applied in specific social contexts. They shape the behaviors and values that individuals internalize, guiding their intuitive understanding and responses in various situations	Articulable, in terms of rules or expectations, may be followed without conscious thought, thereby becoming difficult to articulate.	Hofstede & Hofstede (2005) Schein (2010)
Social Learning	The process of acquiring knowledge through observation, imitation, practice, and social interaction.	Tacit knowledge is often transferred informally in social interactions, enhancing understanding and skills. Allowing for acquisition of insights and practices not be easily articulated, fostering a shared expertise within a community.	Articulable, based on explicit knowledge, also as a result of implicit learning during social interaction.	Bandura (1977) Lave & Wenger (1991)
Pattern Recognition	The process of identifying and interpreting patterns unconsciously in data or situations.	Tacit knowledge influences pattern recognition by helping individuals identify and interpret patterns based on past experiences. Deep, experiential understanding al lows for quicker more accurate recognition of cues in various contexts.	Not articulable, emotional or physiological manifestations can be articulated, not the mechanisms behind.	Simon (1997) Gigerenzer (2008)

Based on the taxonomy of tacit knowledge presented in Section 5.2.1–5.2.11, it is evident that tacit knowledge is a complex phenomenon, closely interconnected with various related concepts (Figure 3 and Table 1). This complexity often leads to overlaps in meaning, prerequisites, and outcomes, making both general understanding and operationalization challenging.

Figure 3. Tacit knowledge and related topics from Sections 5.2.1–5.2.11.

5.3 Tacit Knowledge as a Framework

Given the inherent difficulties in delineating and defining tacit knowledge, it may be more advantageous to conceptualize it as a framework rather than as a singular concept. A framework (Figure 4 and Table 2), drawing on findings from Creswell (2014) and Patton (2002), was therefore developed and applied to address tacit knowledge in terms of its nature (Polanyi, 1966), context (Spender, 1996), acquisition (Kolb, 1984; Nonaka & Takeuchi, 1995), sharing (Leonard & Sensiper, 1998), transfer (Nonaka & Takeuchi, 1995; Collins, 2010), barriers (Boh, 2007; Gourlay, 2016), and application (Sensiper, 1998; Sternberg & Horvath, 1999). This framework captures and highlights the essential characteristics of tacit knowledge, facilitating the development of a more precise and functional definition.

Figure 4. The framework used to delineate and define tacit knowledge, as presented in Section 5.3.

Table 2
Overview of the contextual framework describing tacit knowledge

Framework components	Descriptions	References
Nature	Tacit knowledge is dynamic, evolving, and continuously evolves as individuals encounter new situations and adapt their practices This adaptability is a key feature, enabling individuals to respond to complex, changing environments. Tacit knowledge is furthermore intuitive and non-verbal and is difficult to formalize or articulate, making it distinct from explicit knowledge, which can be codified and shared. Tacit knowledge is described as knowing more than we can tell highlighting the challenge of expressing it in structured or verbal forms.	Eraut (2000) Leonard & Sensiper (1998) Nonaka & Takeuchi (1995) Polanyi (1966)
Context	Tacit knowledge is personal and context-specific and is deeply rooted in an individual's personal experiences and often unique to a particular context. This makes tacit knowledge difficult to separate from the individual, as it is shaped by both personal and situational factors. Context can refer to workplace culture, social settings, or specific tasks that influence how knowledge is applied.	Polanyi (1966) Nonaka & Takeuchi (1995)
Acquisition	Tacit knowledge is experiential, primarily acquired through practice and direct experience rather than formal education or instruction. It emerges through repetitive actions, which are essential for practice and skill development, and is refined over years of hands-on experience—skills that cannot be fully taught in a classroom setting.	Sternberg & Horvath (1999) Leonard & Sensiper (1998 Polanyi (1966)
Sharing	This process emphasizes the interpersonal exchange of tacit knowledge through social interactions and non-verbal cues. This difficulty poses challenges for re searchers attempting to study it, as it may resist codification and measurement, making it inherently resistant to operationalization—expressing the inexpressible is challenging. However, methods such as mentorship, storytelling and demonstration can facilitate the sharing of tacit knowledge, allowing individuals to learn from others' experiences.	Gourlay (2006) Nonaka & Takeuchi (1995) Polanyi (1966)
Transfer	This process involves applying or adapting tacit knowledge to new contexts, ensuring that learned skills and insights are effectively utilized. Another essential characteristic is that tacit knowledge is socially embedded. While personal, it often requires social interaction and shared experiences for effective transfer. Apprenticeships, mentorships, communities of practice, and on-the-job training are environments where tacit knowledge is passed on through close interpersonal relationships.	Lave & Wenger (1991) Nonaka & Takeuchi (1995) Polanyi (1966)
Barriers	Addressing the barriers to tacit knowledge transfer is essential for organizations aiming to leverage their collective expertise effectively. By fostering a culture of trust, implementing continuous and systematic appraisal, and promoting collaboration, organizations can create an environment conducive to sharing and applying tacit knowledge, which, in turn, enhances innovation, problem-solving, and overall organizational performance.	Gourlay (2006) Schein (2010) Nonaka & Takeuchi (1995) Davenport & Prusak (1998)
Application	Moreover, tacit knowledge is action-oriented and is often demonstrated through performance or skills rather than verbal communication and is embedded in the muscle memory and embodied cognition. Furthermore, the application of tacit knowledge extends beyond individuals and is important in collaborative environments, where collective tacit knowledge enhance problem-solving and innovation.	Polanyi (1966) Tsoukas (2005) Nonaka & Takeuchi (1995)

5.4 Defining Tacit Knowledge

Based on Section 5.2–5.3 tacit knowledge has been defined as a framework. Tacit knowledge refers to a deeply personal type of knowledge rooted in individual experience, acquired through informal, often unconscious learning over extended periods. This knowledge is context-specific and challenging to codify, formalize, or communicate, as it is primarily intuitive and unspoken. Tacit knowledge plays a critical role in the development of expertise, emerging mainly from hands-on experience, repetitive practice, and social interaction rather than formal instruction.

Tacit knowledge manifests in various forms, including practical skills, know-how, intuition, procedural knowledge, and embodied cognition—the interplay between body and mind during physical actions. It provides an experience-based, often subconscious understanding of situations, offering a holistic perspective that overlaps with practical wisdom. Due to its deeply personal and experiential nature, as well as its inarticulability, tacit knowledge resists codification and measurement, making it challenging to operationalize in research or formal organizational processes. It is typically demonstrated through action, such as performance or skill execution, rather than verbal or written communication. Since it is embedded in muscle memory and body movements, tacit knowledge is inherently non-verbal and often non-conscious.

Despite its personal nature, effective transfer of tacit knowledge relies on socialization and shared experiences, where trust and interpersonal relationships are crucial. Organizations can foster the dissemination of tacit knowledge by creating environments that promote collaboration, open communication, and systematic feedback. Entities such as communities of practice and mentorship programs are common strategies to facilitate the transfer of tacit knowledge. In this way, organizations enable the collective harnessing of individual expertise, transforming it into organizational expertice.

5.5 Knowledge Transfer in the Pilot Training Program

Based on the findings presented in Papers 1–3, the taxonomy (Section 5.2) and the framework (Section 5.3) of tacit knowledge, as defined, were not clearly observed in the simulator part in the PTP. In contrast to a singular concept of tacit knowledge, various related topics were observed, including implicit knowledge, procedural knowledge, skills, know-how, muscle memory, intuition, reflexes, instinct, cultural norms, social learning, and pattern recognition.

It was challenging to find and observe concepts such as reflexes or instincts in practice, although manifestations of them could occasionally be mitigated through repetitive exposure over time. However, procedural knowledge, skills, know-how, and muscle memory were evident in tasks related to ship handling, such as maneuvering and controlled navigation. Implicit knowledge was also observed, particularly during briefings before, during, or after simulator sessions, where instructors articulated best practices, rules of thumb, or other guidelines. Trainees were continuously immersed in the cultural norms of the pilot trade, the PTP and its supporting organization (SMA), with senior pilots and instructors conveying these norms both formally and informally. Closely related to cultural norms was social learning, which often occurred informally during breaks, meals, or social gatherings and served as a conduit for transmitting various norms. Pattern recognition, closely related to intuition, was observed during ship handling as trainees developed their sensitivity to cues, data, and patterns.

The transfer of tacit knowledge is more prominent in the apprenticeship segment of the PTP, which aligns with the stipulations outlined in the PTP syllabus, particularly through the LTP which embeds trainees in a community of practice at the pilot station. Furthermore, these competencies are systematically trained to a higher standard within the PTP, which is essential for adequately *preparing* trainees and establishing optimal prerequisites for the forthcoming LTP. This includes understanding the characteristics of the piloted ship in different conditions and formulating pilotage plans, as well as contingency strategies. The certification point as an approved pilot signifies a long-term trajectory that marks the development of tacit knowledge.

CHAPTER 6: GUIDELINES ON MARITIME PILOT TRAINING

Drawing on the findings presented in Papers 1–3 and Chapter 5, basic guidelines have been developed to enhance the transfer of tacit knowledge within the simulator part of the PTP. These guidelines are organized into two sections. The first section (6.1) presents guidance for improving the PTP from an organizational perspective, while the second (6.2) presents guidance on enhancing the PTP through research methodologies.

6.1 Organizational Guidelines

- Establish an alumni program: Former trainees, now junior pilots, return for a fixed period after their certification as pilots and serve as mentors for current trainees in the PTP.
- Implement job rotation programs: A set number of junior and senior pilots return as instructors to the PTP, facilitating the transfer of applied experiences from their operational roles.
- Encourage senior trainee involvement: Senior trainees, from the LTP, occasionally return to the PTP to serve as assisting instructors, helping maintain their own progression while mentoring junior trainees.
- Recruit locally tied trainees: Recruit trainees with local ties who are likely to remain in the area over time.
- Schedule regular retiree engagement: Establish a regular schedule for retirees to ensure that the experience of senior pilots is not lost to the organization upon their departure.
- Foster a collaborative peer learning environment: Create an environment where trainees, junior pilots, and senior pilots can share experiences and insights through group discussions and collective problem-solving.
- Implement knowledge-sharing platforms: Utilize forums, portals, or discussion groups to facilitate the exchange of insights and experiences among pilots.
- Develop a knowledge repository: Capture, store, and transfer experiential knowledge, including detailed case studies, best practices, rules of thumb, and guidelines, to preserve valuable information.
- Conduct regular reflection sessions: Facilitate periodic reflection sessions where trainees can discuss their experiences, challenges, and successes to reinforce learning and knowledge transfer.
- Encourage cross-training opportunities: Provide opportunities for trainees to engage in cross-training with other departments or roles within the organization to broaden their perspectives and enhance their understanding of the broader operational context.
- Utilize technology for remote mentoring: Leverage technology to enable remote mentoring and knowledge sharing, allowing pilots on all levels to connect with mentors or experts regardless of location.
- Establish feedback mechanisms: Create structured feedback mechanisms that encourage open communication among trainees, instructors, and junior and senior pilots to facilitate continuous improvement in the training process.

6.2 Research Guidelines

- Implement complementary mixed-methods research instruments: Use a combination of qualitative and quantitative methods to triangulate findings on the types of knowledge being transferred, distinguishing innate functions such as instincts or reflexes from learned processes based on explicit or implicit knowledge.

- Conduct longitudinal studies: Track the development of skills over time to differentiate between learned behaviors based on tacit knowledge and innate responses (e.g., instincts or reflexes), which do not change significantly with the acquisition of expertise.
- Perform cross-cultural comparisons: Evaluate tacit knowledge by analyzing how cultural values and practices influence its development and application, recognizing that it can vary significantly across different cultural contexts.
- Employ ethnographic approaches: Utilize ethnographic methods for in-depth cultural and contextual analysis, thereby enhancing the understanding of tacit knowledge in specific environments.
- Utilize case studies: Explore tacit knowledge within specific organizational settings, particularly in situations where explicit or procedural knowledge proves insufficient.
- Conduct interviews and observations: Collect rich, nuanced data by directly engaging with individuals' experiences and practices, allowing for a deeper understanding of tacit knowledge transfer.
- Incorporate experimental setups and simulations: Use experimental methodologies, including neurocognitive approaches and simulations, to complement traditional qualitative methods. This allows for the controlled manipulation of variables to uncover the cognitive and social processes involved in tacit knowledge transfer.
- Explore machine learning techniques: Leverage machine learning to model and analyze complex data patterns that reflect implicit knowledge structures, facilitating a more sophisticated understanding of tacit knowledge.
- Employ neurocognitive methodologies: Utilize techniques such as functional magnetic resonance imaging (fMRI) or electroencephalography (EEG) to differentiate between reflexes, muscle memory, and e.g., decision-making processes related to tacit knowledge. By comparing brain activity during the execution of automatic motor skills and decision-making tasks, distinctive neural patterns can be mapped, categorized, and linked to their respective cognitive processes.

Chapter 6 has presented guidelines for enhancing the transfer of tacit knowledge within the PTP, both at the organizational level and in terms of improving research on tacit knowledge. The recommendations aim to bridge gaps in current practice by fostering more effective knowledge-sharing mechanisms and refining methodological approaches to studying tacit knowledge in real-world settings.

CHAPTER 7: DISCUSSION

This thesis aimed to enhance the understanding of tacit knowledge and improve its transfer in SCS, particularly in the context of the PTP in simulators, while also utilizing eye-tracking as a didactical tool. In this chapter, conclusions are drawn that summarize the findings from Papers 1–3 and Chapters 5–6. The discussion critically examines how the results align with these aims and explores their implications for future research. To achieve these research aims, three studies were conducted (Papers 1-3), which led to the development of a taxonomy, a framework, and a refined definition of tacit knowledge. These were subsequently compared to relevant aspects of the PTP, culminating in the formulation of guidelines.

This thesis contributes to the enhancement of the PTP, particularly in the context of simulator-based training and the transfer of tacit knowledge. Additionally, the partial exploration of eye-tracking as a didactical tool was examined to improve tacit knowledge management.

7.1 Understanding Tacit Knowledge in Safety-Critical Systems

The overall findings of this thesis highlight the critical importance of knowledge management, particularly within SCS. Tacit knowledge, which manifests in various forms, often lacks a unified understanding or a clear research definition, making it difficult—or even impossible—to fully articulate. As a result, defining and operationalizing tacit knowledge presents two major challenges.

First, tacit knowledge exists in multiple forms, each with varying definitions. These definitions encompass a broad range of concepts, including instinct, intuition, gut feeling, reflexes, know-how, skills, competence, procedural memory, and muscle memory. However, there is often a disconnect between the common or practical interpretations of these concepts and their scholarly definitions. A gap exists between the diverse manifestations of tacit knowledge and the design of research concepts or constructs. This gap, which requires further exploration, is addressed in this thesis through the development of a taxonomy (Section 5.2) that contrasts tacit knowledge with closely related concepts.

Secondly, operationalizing tacit knowledge presents additional challenges. A key difficulty stems from its deeply personal and subjective nature, which makes it difficult for individuals to articulate and difficult for researchers to capture, interpret, and document. Its inherent characteristics resist formalization, hindering the development of metrics or evaluations that could enhance our understanding of its role in knowledge research. This limitation also complicates the transfer of tacit knowledge across organizations, particularly in environments dependent on clear instructions or standardized guidelines. In this thesis, a set of guidelines is proposed to facilitate the transfer of tacit knowledge, focusing on organizational guidelines (Section 6.1) and research guidelines (Section 6.2).

Communities of practice play a vital role in the study of tacit knowledge. However, there is less consensus on whether these communities are formally designed according to set principles or if they evolve organically. Formal communities of practice, such as those found in vocational or apprenticeship programs, integrate both formal and informal social learning. However, attempts to formalize informal methods, such as coffee-break or water-cooler discussions, may reduce their effectiveness, as these interactions are often spontaneous and can be disrupted by formalization. Additionally, these communities sometimes appear more focused on familiarizing trainees with the practices of a community rather than fully integrating them into it.

In SCS, informal initiatives present specific challenges, as they may go unnoticed and result in deviations from established SOPs, potentially compromising safety. This contradicts the primary purpose of SCS, which is to prevent risks and to mitigate the consequences of hazardous events. Balancing informal initiatives that enhance the transfer of tacit knowledge with the associated risks is a delicate task. However, few research efforts have focused on the risks associated with informal social learning in these systems.

Various organizational strategies to address knowledge transfer—such as controlled retirement, retirees returning as instructors, career and retirement planning, recruiting employees from local communities, systematically documenting procedures, implementing job rotation schemes, establishing best practices, and creating knowledge portals—serve as mitigating measures. While these initiatives are valuable, in some cases, replacing outdated, highly specialized equipment or simplifying complex procedures may be more effective than attempting to recreate subject matter expertise or relying solely on organizational mitigations.

A common factor in the effective transfer of tacit knowledge is the role of interpersonal interaction. Connecting individuals with one another may prove more effective than merely providing access to information. Nonetheless, many initiatives aimed at improving tacit knowledge transfer focus primarily on information access, potentially overlooking the importance of human interaction.

This thesis examined the management of tacit knowledge in SCS, highlighting the challenges of defining and operationalizing tacit knowledge, exploring strategies for knowledge transfer, and the significance of situating individuals within a social context.

7.2 Knowledge Transfer

Knowledge creation was observed in various forms in the PTP. In evaluating the simulator part of the PTP, trainees accessed both explicit knowledge—such as course literature, handouts, and slideshows—and implicit knowledge, including verbal guidelines, heuristics, and best practices. Utilizing activity theory, potential tacit knowledge transfer was noted in the simulator part of the PTP, particularly within specific situated learning environments like MRM training. The concept of situated learning highlights the critical role of context in the acquisition and transfer of knowledge.

While the simulator sessions offer valuable experiential learning opportunities, their limited scope may have constrained knowledge transfer. Expanding the range of situated learning contexts could enhance the overall effectiveness of the training program, as observed during the later stages of the LTP. However, this transfer was insufficiently documented in didactic or pedagogical terms within the course syllabi, particularly regarding content. The lack of clear documentation may result in inconsistencies in knowledge transfer, as different instructors may adopt varying approaches based on their interpretations of the material.

Consequently, didactic efforts were managed at the individual instructor level, leading to personalized strategies, especially during post-session simulator briefings. The combination of animations from simulator sessions with whiteboard overlays, where instructors supplemented briefings with their own expertise—such as heuristics and guidelines—however enhanced the effectiveness of these sessions. Instructors possessed a reservoir of implicit knowledge that could be articulated, enriching the briefings and demonstrating that implicit knowledge, while not formalized, can still be effectively communicated. Furthermore, the use of varied teaching styles proved beneficial, exposing trainees to different perspectives and fostering reflection.

This thesis found that knowledge creation involved both explicit and implicit knowledge, with potential tacit knowledge transfer observed in the simulator-based segment, especially in situated learning environments like MRM training. Personalized teaching strategies during post-session briefings enhanced training effectiveness by fostering reflection and exposing trainees to diverse perspectives.

7.3 Eye-tracking as a Tacit Knowledge Transfer Enabler

Eye-tracking provides a tool for capturing, storing, analyzing, and displaying relevant events, providing insights into where individuals focus their attention during learning activities within in the PTP. By examining gaze patterns, instructors can identify which elements of a task or training event present the greatest challenges for trainees, informing the design of training programs to emphasize areas needing further clarification.

While eye-tracking provides valuable data on attention direction, it may not fully capture the learning context or the underlying cognitive processes. Thus, integrating eye-tracking data with other qualitative and quantitative methods is essential for a comprehensive understanding.

Moreover, eye-tracking can reveal the gaze patterns of senior pilots as they perform tasks, allowing trainees to learn how to identify key cues and relevant information that may not be explicitly stated. These cues helps trainees understand how senior pilots interpret and process information, enabling them to adjust their learning strategies. However, it is crucial to recognize that trainees have distinct learning styles, which can influence their gaze patterns and complicate the broader application of expert gaze strategies.

Employing think-aloud protocols alongside eye-tracking while navigating specific routes can effectively inform the design of SOPs for those routes. However, this approach does not account for cross-cultural dynamics and group interactions, which may prevent the SOP derived from eye-tracking data from adequately capturing the intricacies of tacit knowledge and its transfer.

This thesis evaluated eye-tracking as a didactical tool in the PTP. Eye-tracking offers valuable insights into attention by analyzing gaze patterns, helping to identify key elements of interest in training situations. However, it may not fully capture the learning context or cognitive processes and could overlook cross-cultural dynamics and group interactions.

7.4 Types of Knowledge and Transfer Processes in the Pilot Training Program

In the PTP, the MPT conducted in simulators predominantly focused on ship handling, including hydrodynamics, controlled navigation, maneuvering, currents, wind effects, and tugboat operations. These skills are not exclusive to pilots; they are also applicable to mariners in general. However, these competencies are systematically trained to a higher standard in the PTP, which is essential for adequately preparing trainees for the forthcoming LTP.

In Chapter 5, a taxonomy (Section 5.2) was established to enhance the understanding of tacit knowledge and its relation to various related topics. This was followed by the design of a framework (Section 5.3) aimed at better defining tacit knowledge. This definition (Section 5.4) sought to highlight the unique characteristics and implications of tacit knowledge in environments where safety and reliability are crucial, such as SCS. When this framework and the subsequent definition were applied to the simulator part in the PTP, it was discovered that little tacit knowledge was actually transferred. The concepts of know-how and skill exemplify the challenges of observing behaviors related to tacit knowledge. While skills focus on specific technical abilities that are easier to document and transfer, know-how involves the application of these skills in diverse contexts, requiring experience, insight, and tacit knowledge. Such distinctions are critical in both educational and professional settings, as they shape the design of training programs and influence the methods used in the knowledge creation process. Furthermore, this distinction is valuable during the initial stages of research when operationalizing key concepts.

In addition to the methodologies used in this thesis (mixed-methods), employing machine learning to manage, model, and analyze complex data patterns, along with utilizing neurocognitive methodologies to differentiate between various processes based on brain activity, appears promising for further enhancing precision in the study of tacit knowledge.

7.5 Guidelines for Transferring Tacit Knowledge in the Pilot Training Program

The guidelines presented (Sections 6.1–6.2) were designed to enhance the transfer of tacit knowledge within the PTP in general, and specifically during the simulator part. However, applying these guidelines directly to the simulator part of the PTP with a specific focus on tacit knowledge may not fully achieve the desired outcomes. Tacit knowledge transfer is more likely to occur within the LTP, where trainees engage in an apprenticeship environment. This extended exposure to real-world pilotage scenarios is crucial for the development of tacit knowledge. From this perspective, the proposed guidelines should be understood as enhancing the overall understanding of tacit knowledge and its transfer within the PTP, rather than facilitating the transfer of tacit knowledge during the simulator parts of the PTP.

Simulators are effective in conveying explicit knowledge, such as technical skills, procedures, and instructions, as well as implicit knowledge, including knowledge in terms of muscle memory, procedural knowledge, and pattern recognition. However, simulators have limitations in transferring the deeper, experience-based insights that characterize tacit knowledge. The PTP is not inherently an SCS; as previously noted, the simulator parts are designed to prepare trainees for the LTP and for immersion in a community of practice, where tacit knowledge can be more effectively cultivated. Additionally, simulators cannot be relied upon exclusively; they require robust qualitative pedagogical and didactic foundations to be truly beneficial.

Incorporating scenario-based exercises allows trainees to encounter a range of situations, including edge cases, rare events or normal operations, thereby challenging their intuition and their ability to apply acquired knowledge in various contexts. To enhance realism and bridge the gap between simulator-based training and real-world operations, the involvement of senior pilots, experienced ship bridge crews, or even actors could be beneficial. This inclusion would not only increase the authenticity of the training experience but also provide trainees with opportunities to observe and interact with professionals who possess the tacit knowledge necessary for successful navigation in complex environments.

This thesis presented guidelines to enhance the transfer of tacit knowledge within the PTP, focusing on simulator sessions. Both organizational and research guidelines were provided to facilitate this transfer. However, the direct transfer of tacit knowledge is more effectively cultivated in the LTP part of the PTP, where trainees gain extended exposure to real-world pilotage scenarios.

The findings, guidelines, and discussion elements presented in this thesis, along with the author's practical experience as an airline pilot, flight instructor in simulators, and naval officer, extend beyond the PTP and are applicable to other SCS. These insights can be generalized to various domains, such as the aerospace industry, maritime and offshore operations, and the nuclear power industry. This broader applicability underscores the importance of effectively managing tacit knowledge across different sectors, ensuring that critical insights and expertise are shared and utilized to enhance safety and operational efficiency.

CHAPTER 8: CONCLUSION

This thesis aimed to enhance the understanding of tacit knowledge and improve its transfer in SCS, particularly in the context of the simulators, while also utilizing eye-tracking as a didactical tool. In this chapter, conclusions are drawn that summarize the findings from Papers 1–3 and Chapters 5–6.

8.1 Conclusions on Tacit Knowledge in General and Organizational Contexts

- Tacit knowledge transfer is essential for safety and operational efficiency in SCS.
- Tacit knowledge is best understood as a framework encompassing various dimensions, rather than being defined as a singular concept.
- Tacit knowledge predominantly develops within communities of practice, where shared experiences and mutual engagement facilitate deeper learning.
- Tacit knowledge development requires ample time in a profession and is effectively achieved through interpersonal connections, rather than through information dissemination.
- To mitigate knowledge loss, organizations implement measures such as job rotation, rehiring retirees as instructors or mentors, and creating repositories for operational experiences.
- Informal settings may facilitate tacit knowledge transfer, but they also pose potential risks, as they may bypass SOPs and may therefore not be detectable by system mechanisms.
- In certain situations, upgrading equipment or simplifying procedures may prove to be more effective than attempting to recover lost expertise.
- Organizations may adopt a holistic approach to knowledge transfer, implementing strategies such as alumni mentorship programs, job rotation, and collaborative learning environments.
- To study tacit knowledge transfer effectively, organizations should employ mixed-method research designs, conduct longitudinal studies, and gather qualitative data through interviews, supplemented by machine learning and neurocognitive methodologies.

8.2 Conclusions on Enhancements to the Pilot Training Program

- The LTP is essential in the PTP, as immersion in the community of practice fosters tacit knowledge transfer and supports effective progression into their professional roles.
- Simulators are critical for preparing trainees for the LTP, as they provide opportunities to practice and evaluate real-world scenarios within a controlled environment.
- The effective transfer of tacit knowledge depends on interpersonal exchanges; thus, fostering a culture of trust and collaboration is essential for promoting innovation.
- Eye-tracking may enhance trainees' focus on critical information by identifying subtle cues and analyzing eye movements during simulator sessions.
- Eye-tracking can facilitate reflective discussions that enhance knowledge transfer.

8.3. Conclusions and Recommendations for Future Research

- Utilizing mixed methods for triangulation enhances the validity of tacit knowledge studies, and could be further improved by incorporating machine learning or neurocognitive methodologies, such as fMRI, EEG, or other measurement techniques.
- Although eye-tracking effectively captures significant training events, further research is needed to understand its impact on learning processes and the relationship between visual fixation and tacit knowledge.

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