Qualitative Eliciting of Tacit Knowledge in Machinists

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Abstract: Machining, plays a pivotal role in aerospace, medical, and automotive sectors. However, the industry faces labor shortages, exacerbated by the extensive training required for machinists. The learning sciences can elucidate ways to improve such training, addressing labor shortages by optimizing learning pathways for aspiring machinists. Central to this training is the transfer of tacit knowledge—or knowledge with meaning that is rooted in unspeakable tacit dimensions, which is deeply personal, context-specific, and challenging to formalize. With the imminent retirement of experienced machinists, there is an urgent need to capture and transfer this tacit expertise. In this study, part of a broader research to optimize tacit knowledge transmission, we employ qualitative methodologies to understand machinists' tacit knowledge. Leveraging *Generative Knowledge Interviewing* and *Video Stimulating Interviewing*, we trace key constructs into tacit knowledge acquisition in machining such as: socialization, reflective practice, formal learning of machining, sensory tacit knowledge and barriers.

Introduction

Advanced Manufacturing (AM) has significant implications for national security and economic prosperity (White House, 2018), and machining —due to its ability to produce parts characterized by high precision and intricate geometries, which find applications in diverse sectors like aerospace, medical, and automotive automation— stands out as an indispensable manufacturing process. However, the machining industry is grappling with challenges, primarily a widening gap between market and labor demands. This gap is accentuated by a dwindling supply of qualified machinists, a situation that critically hampers the industry's growth potential (Rogers, 2019). Nevertheless, addressing this problem by training new machinists is a resource-intensive endeavor. Traditionally, it takes anywhere between 12 to 24 months of rigorous training or apprenticeship (careers.stateuniversity.com, 2019) before a novice can proficiently handle complex machine operations. This extended period not only demands a significant commitment from experienced trainers but also escalates costs in terms of materials, machine maintenance, and risk factors, especially potential injuries arising from operational errors. Learning sciences can enhance training, helping reduce labor shortages by streamlining learning for future machinists.

The traditional apprenticeship model in machining training primarily focuses on the transmission of tacit knowledge from seasoned machinists to novices. *Tacit knowledge* (Polanyi, 1966), which refers to knowledge with meaning that is rooted in unspeakable tacit dimensions, is characterized by its personal nature and the inherent challenges in formalization and communication. Experienced machinists, for instance, make tool-changing decisions based on a synthesis of auditory and tactile feedback, as well as visual cues such as the shape of the chips produced. With the impending retirement of the current generation of machinists within the next 10-15 years, there is a looming threat of this valuable tacit knowledge being irretrievably lost. While various approaches have been developed to elicit tacit knowledge (Peet, 2012), its inherently implicit, unarticulated, and intuitive nature makes it a challenging effort, especially within the field of machining. Although learning scientists have studied the use of interviews to investigate implicit knowledge in computer programming (Mancy & Reid, 2006), effective methodologies for tracing how tacit knowledge is developed and transferred in the domain of machining can still be more deeply explored from the learning sciences.

Grounded on scholarship that have suggested interview protocols such as *Generative Knowledge Interviewing* (Peet, 2012) and *Video Stimulating Interviewing* (Gubbins et al., 2021), we explored a qualitative protocol to understand machinists' tacit knowledge in US advanced manufacturing. We were guided by the following research questions: (1) How can we elicit tacit knowledge in machining qualitatively? (2) What constructs can be used in a qualitative coding framework to analyze qualitative interviews about tacit knowledge in machining? Through an exploratory approach, we developed an interview protocol that was applied to two machinists, and identified emerging constructs from their interviews and literature review that can be further used to advance qualitative methodologies in this domain.

Background: Qualitative eliciting of tacit knowledge

Polanyi (1966) defined tacit knowledge, stating, 'I shall reconsider human knowledge by starting from the fact that we can know more than we can tell' (p. 4), and highlighting our 'power to know more than we can tell' (1976, p. 336). Tacit knowledge is notably challenging to articulate or codify, as indicated by Nonaka (2007). Individuals possessing this form of knowledge are often unable to explicitly explain the underlying decision-making processes guiding their actions. Polanyi (1962, p. 49) emphasized this point, noting that proficient actions are guided by internalized rules that the individual may not consciously recognize. Furthermore, tacit knowledge is inherently personal and subjective. Nonaka (2007) proposed that there is a cognitive aspect to tacit knowledge, suggesting it is embedded in the individual's mental scripts.

Learning Scientists have considered the richness of interviews to elicit tacit knowledge, and suggested tacit knowledge can be detected through subtle indicators like hesitations and vague language, and it often involves loosely structured, associatively linked ideas that are more easily explained through examples (Mancy & Reid, 2006). Importantly, Peet's (2012) study highlights the efficacy of Generative Knowledge Interviewing (GKI) which emphasizes storytelling and iterative reflection with participants to discern patterns. GKI has proven valuable in identifying and disseminating tacit knowledge among senior organizational leaders, yielding significant immediate cost savings and providing lasting benefits to the organization. Such study also highlights the importance of fostering self-reflection and curiosity among professionals, aligning with previous research that emphasizes the need for educating "reflective practitioners" (Schon, 1983) capable of critical self-examination and proactive learning. Similarly, van Braak et al. (2018) uses Reflective Video Stimulated Interviewing (VSI) (Van Tartwijk et al. 2009) as a tool for uncovering implicit routines in real-world settings.

Methods

The methodology involved interviews with two machinists, including a 5th-year Ph.D. student in manufacturing engineering with five years of experience and a machine shop manager with over twenty years of manufacturing experience. Based on previous approaches to eliciting tacit knowledge qualitatively, we combined van Braak et al. (2018) application of VSI and Peet's (2012) GKI to create a think-aloud interview protocol that could be used either after a machinist performs a machining task or while watching a video recording of themself doing such task. The rationale for doing the think-aloud interview not strictly during the machining task relies on the safety of the interviewer and the machinist, since then these tasks often require safety measures that need to be met. Following the initial interviews and analysis, our research process involved two comprehensive rounds of qualitative coding to further distill and understand the nuances of tacit knowledge within the context of machining. Here, we adopted a collaborative coding approach. Both coders, each with their unique expertise — one in the learning sciences and one in machining — worked together, discussing and negotiating the use and meaning of each code to reach consensus. This reflexive method allowed us to co-construct the analytical narrative, ensuring our thematic development was consistent and validated through mutual agreement, thereby maintaining methodological integrity.

In the first round, we employed a deductive coding approach, actively searching for constructs previously identified as pivotal in the acquisition and transfer of tacit knowledge. This structured approach allowed us to categorize and analyze the data based on established frameworks and theories, ensuring a rigorous and systematic examination of the tacit knowledge embedded in machining practices. In the subsequent round of coding, we shifted our focus to an inductive approach, allowing themes and codes to naturally emerge from the interview data. This phase of analysis brought to light additional aspects of tacit knowledge not initially anticipated, including insights into the participants' formal learning experiences in machining, their engagement in reflective practice (Schon, 1983) , and the multimodal nature of tacit knowledge acquisition.

Results

The first outcome of this process was the emergence of a framework and interview protocol to elicit tacit knowledge in machining qualitatively. The resulting protocol consisted in two parts: First, a *think-aloud interview* during the observation of a video recording (van Braak et al., 2018) or immediately after the machining task. The participant will be asked to verbally express and reflect on the steps of the task, the decisions taken, and the sensory inputs that led to or informed those decisions. In this part, the researcher also observes how the machinist interacts with the machine, the workpiece, and the environment, looking for non-verbal and multisensorial cues that guide the machinist. Second, a *traditional qualitative interview*, in which machinists will be interviewed through a set of twelve questions. Both parts of the interview were coded, resulting in the identification of the following five topics:

Formal learning of machining

Individuals' experiences and processes in acquiring and refining their machining skills. This encompasses hands-on interactions with various types of machinery such as hybrid, CNC, and manual machines, as well as theoretical learning related to machine operation and programming. For example:

> "I started doing research, with the hybrid, CNC and manual machine, and just by the nature of the machine, I had to learn G code and programming and things like that learning how to run a CNC machine. So ever since then, I've been picking up little tips and tricks here and there. It was some resources here, I took lessons from him on how to run these machines."

The machinist's journey exemplifies formal learning in machining, blending theoretical knowledge like G code and programming with hands-on experience across different machines, demonstrating a continual progression in skill proficiency.

Sensory tacit knowledge

Describes instances when a machinist implicitly acquires knowledge and expertise through hands-on experience in machining. It also highlights the incorporation of various sensory and physical cues, such as auditory signals from the machinery and materials, as well as the shapes, colors, and textures of the materials, in the learning process. For instance:

> "Usually, usually it comes down to like sound or sight. and sight is a little bit harder because either you're running coolant and you really can't see what's going on or your machine you've got enclosure under CFCs you can see what's going on."

Here, reliance on auditory and visual cues, despite challenges like coolant or machine enclosures, illustrates the acquisition of sensory tacit knowledge, where sound and sight play critical roles in understanding and mastering machining processes.

Socialization

Refers to the processes through which tacit knowledge is transmitted and shared among members of the community of practice (Lave & Wenger, 1991) of machining including informal learning, mentoring, and social networks.

> "I texted Adam and other PhD students I said hey, are you cool if I start digging into this and so I started opening panels up and we found that it was just one of the solenoids or for the a axis stopped working just until I took it apart I think that put it back together started working fine again."

Interaction with peers, like consulting other PhD students, exemplifies socialization in machining, where sharing and solving problems collaboratively plays a key role in the transmission of tacit knowledge within the community.

Reflective practice

Refers to the use of critical reflection to examine and evaluate one's own tacit knowledge and practices, with the goal of improving performance and generating new insights (Schon, 1983).

> "So part of it is or a break or two or whatever things oftentimes you can get you're not running, catch it before that happens. Because it goes to cut the side and it doesn't cut hardly anything, you have to think for yourself like "Oh, is there something wrong with my program or something amiss with my setup."

Reflective practice (Schon, 1983) is highlighted as the individual critically evaluates potential issues in machining tasks, like program errors or setup mishaps, showcasing deep self-assessment and proactive thinking aimed at continuous improvement of performance and skills in their craft.

Barriers

Refers to the factors that facilitate or impede the acquisition, sharing, and application of tacit knowledge, including individual, organizational, and contextual factors (Chugh, 2018).

> "You get a really good look at how the CAM side of things works when you actually go to programs. But you don't get a great understanding of how the tool will interact with the material, because I can program anything to make a shape. But will it actually cut and not destroy the tool? Is it going to rip my part on the device? … So you don't really get that unless you're in front of the machine or on making parts making chips."

This quote underscores barriers in machining knowledge acquisition, highlighting the gap between programming skills and understanding tool-material interaction. Practical, hands-on experience is essential for learning outcomes that can't be fully grasped through theoretical programming alone.

Discussion

This exploratory study centers on the need for a qualitative protocol to elicit tacit knowledge in machining, probing how this implicit knowledge is communicated and utilized. By interviewing two experienced machinists using a think-aloud protocol based on *Generative Knowledge Interviewing* and *Video Stimulating Interviewing*, the study identified key themes such as the value of hands-on learning, sensory cues in skill acquisition, and the importance of social learning networks. Moreover, *reflective practice* (Schon, 1983) emerged as a vital tool for machinists to evaluate and enhance their practice. The findings emphasize the need for a holistic approach to machinist training that bridges the gap between academic concepts and practical applications, and fosters a learning environment tailored for novices, which opens the door for simulated environments such as Augmented Reality (AR) and Virtual Reality (VR) to help bridge these gaps and thus facilitate safer, more efficient learning experiences. In future studies, the learning sciences can inform advanced training in higher education, leveraging the design of AR and VR tools to improve hands-on skill acquisition.

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