The Effect of Implicit Knowledge on Situation Awareness in the Asphalt Construction Industry

Master Thesis

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Keywords:

situation awareness, implicit knowledge, asphalt construction industry,
roller operator, virtual reality,

Word Count: 22.019
October 4, 2024

Acknowledgment

I want to take this opportunity to thank everyone who has supported me throughout this journey. First and foremost, I would like to thank my supervisor Ilona Friso-van den Bos as her guidance and feedback consistently allowed me to improve my research. The results that I present today, would not have been possible without her and I owe much of the quality of this product to her. Secondly, I would not have had the opportunity to write this Thesis, let alone do this Master's Degree, if it was not for my amazing employer. Frank, you are my manager and my colleague, but above all, you are my friend, and I appreciate the lengths that you and SMS have gone to allow me to study at the University of Twente. Quite similarly, I want to thank Lianne, Kaj, and Milan as well, it would be difficult to find more supportive colleagues than the three of you. Thirdly, I want to thank Luca Frosler and Lorette Bosch-Padberg from the BMS lab. They tinkered with the roller simulator, gave me the necessary software, and allowed me to use the Experivan to travel all of Gelderland in search of participants. Finally, I want to thank my family and friends for all the support they have given me throughout the years. Specifically, I want to thank my parents who had to drag me out of my room sometimes, so I would not study for entire days. Also, I cannot finish this section without mentioning my friend Tim who always encouraged me to knock it out of the park. Even if I felt overwhelmed or unmotivated, you would tell me to get it done, and I can only say: Thank you!

Abstract

Within the asphalt construction industry roller operators need good situation awareness to compact roads properly. They need to take the characteristics of the asphalt and the conditions of the atmosphere into account while they operate their roller. Currently, experienced roller operators rely on their inherent skills and past working experiences to perform their job well. This study investigated the impact of implicit knowledge on situation awareness, to discover if the implicit knowledge of experienced operators explains their enhanced situation awareness. To answer the research questions of this study a mixed method design was used. Participants controlled a virtual roller within a virtual 3D environment to measure their situation awareness. Afterward, the knowledge and decisions of the participants were questioned through stimulated recall interviews. The results indicate that there is a positive relationship between experience and situation awareness, as the overall situation awareness scores of the experienced participants were significantly higher. The experienced operators did not score significantly higher for each individual level of situation awareness as they only scored significantly higher for the level comprehension. The high situation awareness scores of the experienced participants could however not be attributed to implicit knowledge. During the interviews, a wealth of explicit knowledge was communicated to the researcher, but only small fragments of implicit knowledge were found. Most experienced participants were more than capable of articulating why and how they made certain decisions. Future research could focus on extracting specific knowledge from roller operators by enhancing the virtual 3D environment.

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1. The Effect of Implicit Knowledge on Situation Awareness in the Asphalt Construction Industry

Situation awareness is an individual's understanding of the world that surrounds them, which is essential for making decisions in dynamic environments (Endsley, 2006). Accurately assessing a situation, and anticipating how it will develop, increases the odds of making a good decision. Within the asphalt construction industry, vocationally educated roller operators work in dynamic environments that shape their decision-making. Paving a road may look simple from the outside, but roller operators have to make real-time decisions based on the asphalt that surrounds them, the weather, and various other dynamic elements (Makarov et al., 2023). Moreover, minor mistakes have adverse effects and influence the quality of newly paved roads (Bijleveld, Miller, De Bondt, et al., 2015). Therefore, experienced roller operators have to pay attention to the asphalt that surrounds them to ensure the correct density requirements are met and inconsistencies and defects are prevented (Hand et al., 2021). Much of this knowledge is, however, implicit, gained individually through time (Bijleveld, Miller, & Dorée, 2015), and often expressed unintentionally during task performance (Yordanova et al., 2008). As a result, there is a knowledge gap between experienced and inexperienced roller operators. Implicit knowledge plays a large role in this, but it is difficult for experienced roller operators to verbalize the implicit knowledge they possess (Bijleveld & Dorée, 2014). The presence and importance of implicit knowledge within the construction industry has been researched and confirmed (Z. Zhang et al., 2023). However, differences in situation awareness between experienced and inexperienced roller operators have not been studied yet. Furthermore, the impact of implicit knowledge on the situation awareness of experienced roller operators has not been assessed either.

This study started precisely here, as implicit knowledge may improve the situation awareness of experienced roller operators. On the one hand, this study contributed to existing scientific literature (Z. Zhang et al., 2023) by continuing the research on the potential effects of implicit knowledge on situation awareness. On the other hand, the findings of this research provided an explorative insight into the implicit knowledge of experienced roller operators which is valuable for practitioners. These insights are crucial within this industry, as the field of asphalt compaction is already heavily reliant on the implicit knowledge and operational skillsets of experienced roller operators (Bijleveld & Dorée, 2014; Makarov et al., 2023). It must be noted as well that these experienced roller operators will not be around forever. Zippia (2024) captures the demographics of most jobs in the US and over 64% of the roller operators in 2024 were 40+ years old. Younger generations of roller operators will have to go through the same individual, lengthy learning cycles, unless more attempts are made to tap into the knowledge of experienced operators (Bijleveld & Dorée, 2014). As a result, the effects of implicit knowledge on situation awareness were investigated to further emphasize the importance of implicit knowledge. The following research question was at the heart of this study: "*How does the situation awareness of experienced roller operators differ from those of inexperienced operators, and what role does implicit knowledge play in this difference?*".

To answer this research question theory surrounding implicit knowledge and situation awareness was investigated. Based on this theory hypotheses were formulated and subsequently a methodology section was developed. First and foremost, a state-of-the-art virtual 3D environment was used to measure the situation awareness of both experienced and inexperienced roller operators. As a result, the study was able to measure the situation awareness of 19 roller operators without having to use an actual tandem roller and expensive resources. Secondly, these roller operators also participated in stimulated recall interviews, where they explained why and how they made certain decisions.

2. Theoretical Framework

2.1. Situation Awareness

This chapter examines the concept of situation awareness by describing its importance and defining the concept accordingly. Subsequently, the concept is visualized through Endsley's (1995b) model and the process of developing situation awareness in a given situation is investigated too. Finally, the importance of situation awareness within the asphalt construction industry is discussed.

2.1.1. The Importance of Situation Awareness

Within various professions employees make decisions that require an accurate analysis of the environment (Endsley, 1995b). Within dynamic and complex environments (e.g. air traffic control) things can change rapidly and as a result new choices often emerge that require new decisions which need to be made. This is where situation awareness comes into play, as this is a subject's up-to-date understanding of the world that surrounds them (Endsley, 2006). This understanding should be seen as an internal cognitive phenomenon according to Salmon et al. (2012), to a certain personal extent a subject is aware of various elements within their environment. Consequently, one's awareness of these elements actively influences the decisions that are made, and these decisions influence the quality of one's overall performance (Endsley, 1995b). Simply put, an up-to-date understanding of the environment leads to better performance and decision making (Endsley, 2006). As a result, researchers have investigated situation awareness for over 30 years in various dynamic and complex environments, to compare, understand, analyze, and improve the performance of participants. Therefore, situation awareness has become a relevant topic for research in a wide variety of dynamic and complex environments (Endsley, 2015), like military aviation (Carretta et al., 1996; Endsley, 1995a), driving (Gugerty, 1997; Jóhannsdóttir & Herdman, 2010), healthcare (McKenna et al., 2014) and construction (Hasanzadeh et al., 2018). This increase in overall research on situation awareness throughout the years is a testimony to the importance of the theoretical construct in scientific literature and among practitioners (Wickens, 2008).

2.1.2. Defining Situation Awareness

There is no scientific definition of situation awareness upon which every researcher agrees. Individual researchers define the concept differently and these definitions often lead to contention in various scientific journals (Stanton et al., 2017). Ultimately, some definitions have become more popular than others within scientific literature (Stanton et al., 2017), and arguably the most popular definition is from Endsley (1988). She defined situation awareness as one's *perception* and *comprehension* of various elements within the environment and the *projected* status of those elements in the future. This definition contains three distinct levels that are a part of Endsley's (1995b) model (see Figure 1): perception, comprehension, and projection.

Perception is the ability of a subject to perceive important elements within their environment. Perception extends beyond visual input and encompasses other senses, such as hearing and touch as well (Endsley, 2006). Elements that a roller operator may perceive at any given time are the speed of their roller or the condition of the weather. It is important to note that at this level no further considerations are being made based on the elements that were perceived. Whether the condition of the weather is good or bad is not being considered yet. Comprehension is the ability of a subject to interpret the meaning and significance of the elements that were perceived. At this level, various disjointed elements that were perceived are combined to comprehend the current situation (Endsley, 1995b). A roller operator may realize that they are driving too fast for the type of asphalt that they are paving. In this example multiple separate elements are combined and their significance was assessed. When a subject predicts what will happen to these elements in the future they arrive at the final level of situation awareness, projection. This ability to forecast future events requires a high level of understanding of the current situation (Endsley, 2006). The roller operator predicts that at the current speed, the asphalt will not achieve the desired density, and as a result, the speed of the roller must be adjusted. Based on this projection the roller operator made a well-informed decision. As a result, the three distinct levels of Endsley's (1988) definition can be illustrated with a simple example. A roller operator with a high level of situation awareness would perceive a change in the weather and comprehend that the incoming rain will increase the rate at which the asphalt cools down. Therefore, the operator projects that their current speed may not be sufficient to compact the remaining asphalt at an acceptable temperature. Consequently, the operator decides to speed up their roller to seven kilometers per hour in response to the rain.

It must be noted however that the examples that have thus far been provided to illustrate the various levels of situation awareness have been simplified to a certain degree. Various individual or task related factors impact this process and reduce (or improve) a subject's situation awareness (Endsley, 1995b). Raestrup (2023) for example, investigated the effects of time pressure and stress on the situation awareness of roller operators. Based on various theories she assumed that more time pressure and stress would result in lower situation awareness scores. Conversely, she saw an unexpected increase in the situation awareness scores of participants when there was more time pressure and stress involved. This example illustrates that various factors can influence situation awareness in unexpected ways. As a result, these factors form an important part of Endsley's (1995b) model of situation awareness.

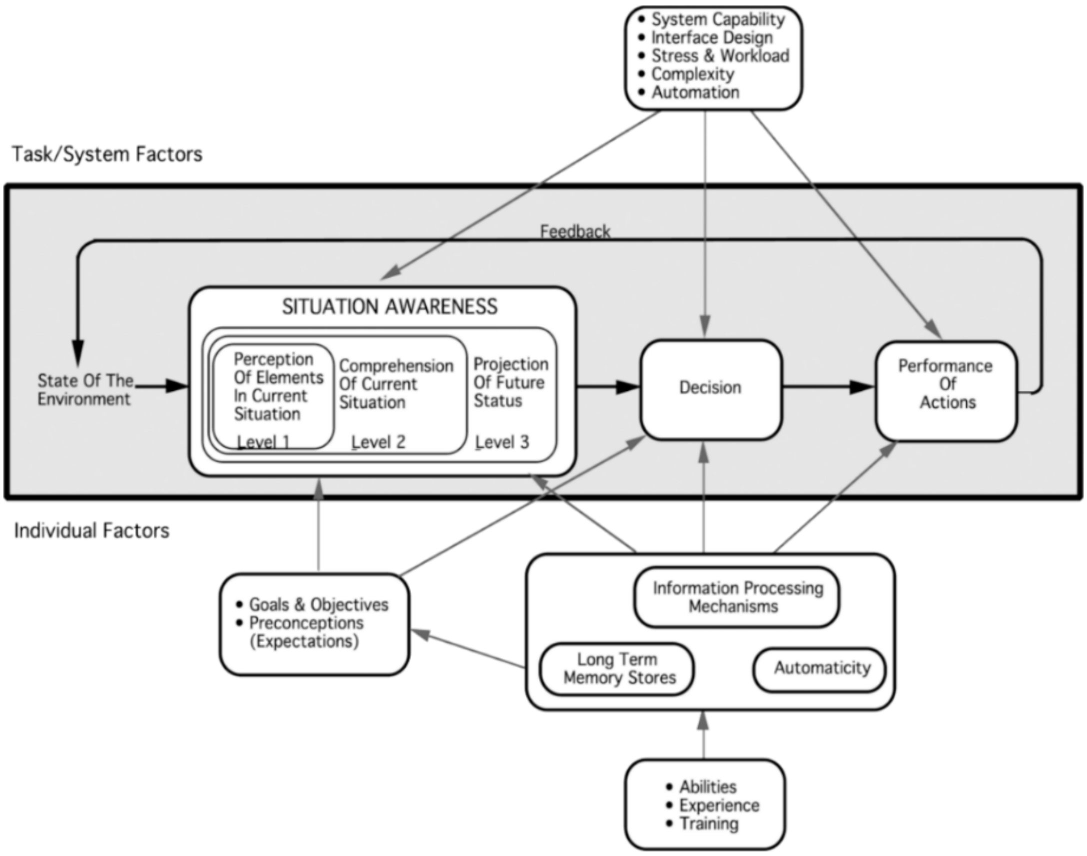
2.1.3. Endsley's Model of Situation Awareness

Endsley's (1995b) model of situation awareness (see Figure 1) depicts how the three levels of situation awareness and various factors interact with one another. Multiple models that illustrate situation awareness have been introduced over the past 30 years within scientific literature (Endsley, 2000). However, Endsley's (1995b) model of situation awareness still holds a prominent place within most fields (Wickens, 2008). A recent literature review from Ofte and Katsikas (2023) confirms the trend that research is still often based on Endsley's model (1995b).

As with most conceptual models, Endsley's (1995b) model of situation awareness has not gone without critique. Salmon et al. (2012) for example questioned the linearity of the model and the way the various elements of situation awareness interact with one another. Many of these concerns have been addressed over time (Endsley, 2015), and most initial questions about the model have been laid to rest. Therefore, the decision was made to use Endsley's model (1995b) of situation awareness (see Figure 1) for this study.

Figure 1

Endsley's Model of Situation Awareness



2.1.4. Developing Situation Awareness

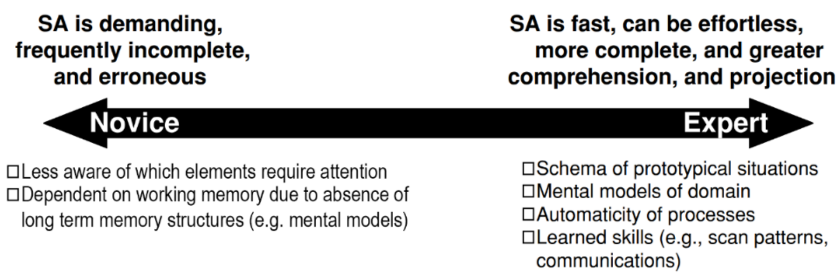
2.1.4.1. Developing Situation Awareness during a Single Situation. Situation awareness is an internal cognitive phenomenon (Salmon et al., 2012), in a certain situation individuals can become aware of their environment by using their senses. It can be described as coupling yourself mentally to an environment and its dynamics (Stanton et al., 2017). Therefore, situation awareness is often not acquired instantaneously, one's understanding of a given environment develops over time (Endsley, 1995b). A practical example of this is a busy intersection during rush hour, a driver is not instantaneously aware of every other sign, vehicle, and pedestrian. Dynamic situations, like these busy intersections, constantly change and therefore a driver must remain aware (Endsley, 2000). This is also illustrated by Endsley's (1995b) model (see Figure 1), there is a dynamic feedback loop, as information is gathered continuously and used to make decisions. These decisions can change the situation drastically and as a result the 'state of the environment' needs to be assessed again. Furthermore, familiarity with a specific situation does not make situation awareness irrelevant. No matter how many times a driver has passed that same busy intersection, every time they reach this intersection, they will have to become aware again of their surroundings. However, having a lot of experience with this specific intersection can help, as a driver will have learned through time, what elements they should pay attention to. The examples above illustrate that situation awareness has to be developed and maintained for every dynamic situation (Endsley, 2006).

2.1.4.2. Developing Situation Awareness Over Time Through Experience. Numerous studies in multiple fields have found a positive relationship between experience and situation awareness (Cak et al., 2020; Carretta et al., 1996; Endsley, 2006; Hyun et al., 2006; Pammer et al., 2021). According to Endsley (2006), experience in a given field leads to the development of various cognitive concepts that support the development of situation awareness (see Figure 2). One such example of a cognitive concept is 'automaticity', which is also mentioned in Endsley's (1995b) Model (see Figure 1). If an experienced driver can perform every physical action (e.g. operating the clutch) autonomously, more attention can be concentrated on the surroundings. In that regard, the automaticity of physical tasks positively impacts situation awareness (Endsley, 2006), although Van Benthem and Herdman (2020) found no association between experience and the highest level of situation awareness. It is experience that often leads to the development of cognitive concepts that impact situation awareness. Numerous studies have researched the impact of various cognitive concepts on situation awareness like: cognitive abilities (Sohn & Dattel, 2001), automaticity (Endsley, 2006), attention strategies (Hasanzadeh et al., 2018), mental models (Endsley, 1995b), and complex memory structures (Randel et al., 1996). Because these mechanisms develop through experience, Endsley (2016) and Brockmann and Anthony (2002) agree that situation awareness is developed on the job, since real experiences create expectations for future events. According to Evers and Van Der Heijden (2016) it takes a considerable amount of time for someone to become proficient in their field. This might explain why situation awareness scores often vary so much between experienced and inexperienced participants. The study of Hasanzadeh et al. (2017) for example used eye-tracking to analyze if experienced construction site workers were more situationally aware than their inexperienced counterparts. Experienced workers appeared to be more situationally aware, as they optimized their attention and distributed it across the construction site (Albert & Hallowell, 2012). In summary, experience impacts the development of situation awareness, as experience leads to the development of underlying cognitive concepts that improve the overall development of situation awareness (Endsley, 2006).

2.1.4.3. Developing Situation Awareness Through Cognitive Concepts. Various studies state the importance of experience and subsequently name an underlying cognitive concept that supports the development of situation awareness. Extensive research on situation awareness has been conducted among pilots, encompassing both military and commercial aviation. As a result, many articles identified a wide range of important cognitive concepts that influence the situation awareness of pilots. Endsley (2006) for example concluded that high levels of situation awareness can only be achieved if a pilot no longer needs to concentrate on the physical tasks they need to perform (automaticity). O'Hare (1997) states that cognitive abilities are more important than physical skills. Finally, Cak et al. (2020) and Sohn and Doane (2004) found that working memory is essential for good situation awareness. While experience undoubtedly contributes to the development of situation awareness, an ongoing debate persists among researchers regarding the cruciality of various underlying cognitive concepts.

Figure 2

Factors that Affect Situation Awareness in Novices and Experts



Note. The bullets on the left were adjusted to illustrate the impact of being a novice, for the original image consult Endsley (2006, p. 637).

2.1.5. Importance of Situation Awareness for Roller Operators

Roller operators need to make real-time decisions under time pressure (Makarov et al., 2023) and they need to accurately assess elements (e.g. the thickness of the asphalt) within their working environment (Bijleveld, Miller, & Dorée, 2015). As a result, roller operators need good situation awareness. A roller operator cannot compact a road properly unless they take multiple factors from their environment into account like the weather or the asphalt mixture (Bijleveld & Dorée, 2014). This can be challenging as roller operators need to make these decisions whilst they are operating their roller. More importantly, key parameters (e.g. the decrease in temperature of the asphalt mixture (Miller et al., (2011)) are often not available as road construction processes are generally carried out without high-tech instruments (Bijleveld, Miller, & Dorée, 2015). To exacerbate the situation further, there is a low margin for error within this industry (Makarov et al., 2023); incorrectly compacting asphalt has adverse effects. The life span of the asphalt will be reduced, and the asphalt will be less resistant to cracks and fractures (Bijleveld, Miller, De Bondt, et al., 2015). Additionally, the costs of repairing these mistakes are excessive (Bijleveld et al., 2012). Researchers have started to develop trajectory planning software to support the situation awareness of roller operators and reduce the variability in quality of compacted asphalt (Makarov et al., 2023). This software suggests real-time trajectories based on the characteristics of the atmosphere and the asphalt. Rollers with this software reduce the number of factors that a roller operator needs to take into account. However, additional tests on actual construction sites are necessary before this software can be used within the industry. Right now, experienced operators have to assess important elements (e.g. asphalt temperature) within their environment to determine the best approach. These estimates often vary wildly as each roller operator may be aware of different elements within their work environment to make a decision (Bijleveld & Dorée, 2014). Experienced roller operators have a clear advantage, they can draw upon past experiences to make a decision when they analyze their work environment. Inexperienced roller operators do not have this luxury yet, they may not be aware of various elements and their importance. Based on the above it was hypothesized for this study that experienced roller operators would have better situation awareness than their inexperienced counterparts. This hypothesis aligns with the findings of existing studies from various fields that researched the effects of experience on situation awareness (Cak et al., 2020; Carretta et al., 1996; Endsley, 2006; Hyun et al., 2006; Pammer et al., 2021). Various cognitive concepts could be responsible for this hypothetical difference in situation awareness. The next chapter investigates implicit knowledge and its potential impact on situation awareness, as implicit knowledge is an important cognitive concept for roller operators (Bijleveld & Dorée, 2014; Makarov et al., 2023).

2.2. Implicit Knowledge

This chapter examines the cognitive concept of implicit knowledge. Firstly, both implicit and explicit knowledge are defined. Subsequently, the difficulties surrounding articulating and detecting implicit knowledge are formulated. Finally, the connection between implicit knowledge and situation awareness is investigated and the role of implicit knowledge within the asphalt construction industry is assessed as well.

2.2.1. Defining Implicit and Explicit Knowledge

Within scientific literature descriptions of implicit and explicit knowledge have remained quite similar throughout the years. In general, most researchers agree that implicit knowledge is difficult to verbalize (Hélie & Sun, 2010; Hulstijn, 2005; Roehr-Brackin, 2022) and that we are little or not at all consciously aware of the implicit knowledge that we possess (Hulstijn, 2005; Schacter, 1990; Yordanova et al., 2008). Furthermore, the use of implicit knowledge does not require many attentional resources (Hélie & Sun, 2010) as implicit knowledge is used automatically to perform a task at hand (N. C. Ellis, 2005; Segalowitz, 2003). A practical example of this would be the clutch of a vehicle, which many experienced drivers operate automatically without any deliberate thoughts attached to it. The procedures that are used to operate the clutch are retrieved automatically, this is why some researchers refer to implicit knowledge as procedural knowledge (Anderson, 1996; Segalowitz, 2003). By synthesizing the descriptions of implicit knowledge from various researchers, the concept of implicit knowledge can be defined as knowledge that we are not consciously aware of. Therefore, this knowledge is difficult to verbalize and is used automatically without any attentional resources. Explicit knowledge, on the other hand, is often described as knowledge that we are consciously aware of, and therefore this knowledge is easier to verbalize (R. Ellis, 2004; Hulstijn, 2005; Roehr-Brackin, 2018). Additionally, the use of explicit knowledge may require attentional resources (Hélie & Sun, 2010) as various thoughts (that can be declared) still come into play to perform a task at hand. This is why declarative knowledge is sometimes used as a synonym for explicit knowledge (R. Ellis, 2004; Sun et al., 2001) since explicit knowledge can be represented declaratively (Roehr-Brackin, 2022). Because explicit knowledge can be articulated it can also be written down, stored, and later on accessed. This is why documents (e.g. a manual) are often considered explicit knowledge as well (Nonaka et al., 2000). Based on the above, explicit knowledge can be defined as knowledge that we are consciously aware of, and therefore, this type of knowledge can be verbalized and shared with others through various means. The above definitions may give the impression that implicit and explicit knowledge are two distinct categories, as knowledge either belongs to one or the other. Both types of knowledge should however not be regarded as dichotomous, but rather they are situated on a scale (Mancy & Reid, 2006; Roehr-Brackin, 2022). Even though both types of knowledge are sometimes studied in isolation (Sun et al., 2005) various studies confirm that explicit knowledge can become implicit over time, and vice versa (R. Ellis, 2004; Hélie & Sun, 2010; Segalowitz, 2003; Sun et al., 2001). Since it is difficult to verbalize implicit knowledge the next section assesses what can be done to elicit deeply ingrained implicit knowledge.

2.2.2. Verbalizing Implicit Knowledge

Placing the conceptualizations of implicit knowledge and explicit knowledge on a scale as suggested by Roehr-Brackin (2022), supports the idea that there are various degrees of implicitness. This is in line with the findings of Ambrosini and Bowman (2001) who believe that some implicit knowledge will be too deeply ingrained to expose, but there is implicit knowledge that could be articulated to a certain extent. There are various elicitation techniques (Barton, 2015) that are designed to do just that, expose as much implicit knowledge as possible with the help of stimuli. Stimuli can be photos (Barton, 2015), video materials (Lyle, 2003) or drawings (Kothari et al., 2012), which support the elicitation of otherwise inaccessible knowledge. These stimuli are often used in conjunction with neutral open-ended questions (Lyle, 2003; Van Braak et al., 2018). Firstly, these questions are neutral for a reason, as leading questions can contaminate the thought processes of participants (Paskins et al., 2014). Secondly, these questions are generally open-ended as questions that produce simple “yes” or “no” answers fail to expose the intricacies that resulted in an answer. As a result, researchers often use probing questions and stimuli to encourage participants to articulate information that would not be articulated under normal circumstances (Barton, 2015). For example, Paskins et al. (2017) recorded consultation sessions between general practitioners and patients. The recordings were later on used as stimuli and shown to the general practitioners during interviews. The researchers asked various probing questions to learn more about the thoughts and intentions of each participant. The results of this study indicated that the general practitioners were able to give specific in-depth responses with the help of the recordings, which allowed them to provide meaningful explanations of their behaviour during the consultation sessions.

Within the asphalt construction industry attempts have been made as well to explicate implicit knowledge. So far, Bijleveld and Dorée (2014) found that it was difficult for roller operators to articulate the implicit knowledge they possess. This is not surprising, as implicit knowledge is a highly personalized asset (L. Zhang et al., 2013). As a result, it was hypothesized for this study that experienced roller operators would struggle to explain their decisions and verbalize their knowledge due to their reliance on implicit knowledge. The next section will explore what makes implicit knowledge such a uniquely personalized asset.

2.2.3. Developing Implicit Knowledge

Implicit knowledge is a valuable personal asset because it develops over time through various means. Firstly, explicit knowledge gradually transforms into implicit knowledge as individuals continuously practice and apply the knowledge that they possess (Smith, 2001). Over time, this knowledge becomes more embedded in the individual as it becomes more personal, intuitive, and contextual (Van Houten, 2023). It must be noted that this process frequently occurs automatically, as the individual is not always aware that they are quietly improving their skills and knowledge, this process is often described as implicit learning (R. Ellis, 2009; Roehr-Brackin, 2022). Secondly, implicit knowledge often develops through social interactions with surrounding colleagues (Van Houten, 2023). While individuals may not purposefully share their implicit knowledge, it is often transferred through the stories, metaphors, and advice they share with each other (Krátká, 2015; Van Houten, 2023). Research from Javernick-Will (2012) indicates that social motivations often fuel this desire to share stories or advice as individuals want to be recognized by their peers and support their teams. Thirdly, the development of implicit knowledge can also be influenced by reflective practices. As reflecting on important work experiences enables individuals to comprehend and assimilate the insights they have acquired (Smith, 2001; Van Houten, 2023). The aforementioned points demonstrate how implicit knowledge develops over time. Since it is difficult to articulate implicit knowledge the next section will cover how researchers can recognize implicit knowledge during a conversation.

2.2.4. Detecting Implicit Knowledge

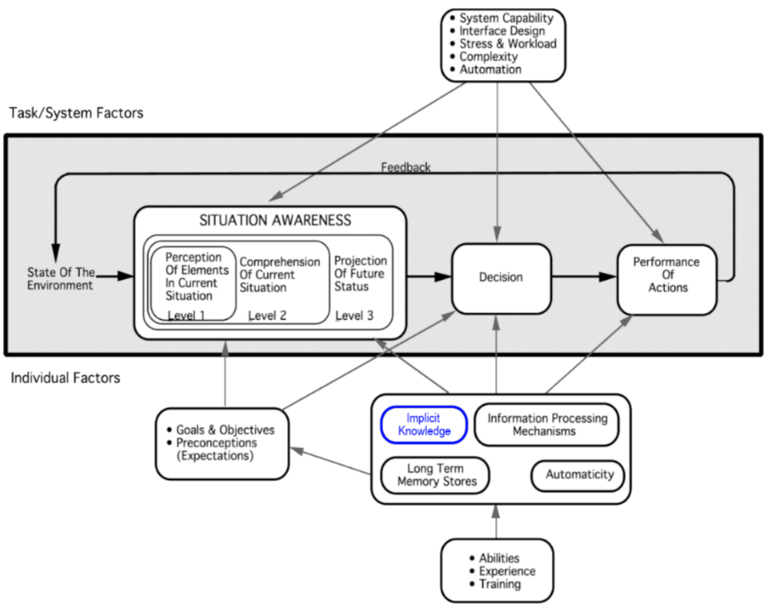
Using the aforementioned stimuli (Barton, 2015) and neutral open-ended probing questions (Van Braak et al., 2018) will lead to various answers from participants. To determine which answers contain implicit knowledge, researchers can pay attention to various cues according to Mancy and Reid (2006). In their study they concluded that there are five cues in the answers of participants that may help to determine if the knowledge a participant expressed was implicit. For example, a participant may not be able to explain how they utilized a skill or why they made a certain decision for example. However, they did achieve success with this particular skill and it was used correctly. This is an indication of implicit knowledge according to Mancy and Reid (2006), as a particular skill was used without any conscious deliberation. Likewise, a participant may not be able to coherently formulate the knowledge they have, instead, they rely on concrete examples (Mancy & Reid, 2006) or metaphors (Ambrosini & Bowman, 2001) to answer questions. As a result, concrete examples are used as the actual knowledge of the topic cannot be verbalized as it is too implicit.

2.2.5. Implicit Knowledge and Situation Awareness

Implicit knowledge is not explicitly mentioned in Endsley's (1995b) model of situation awareness. However, various individual factors of the model are positively influenced by implicit knowledge. According to Endsley (1995b) automaticity benefits situation awareness as tasks can be performed automatically without any conscious awareness. Implicit knowledge often allows people to perform tasks automatically (N. C. Ellis, 2005; Segalowitz, 2003) without having to spend any attentional resources (Hélie & Sun, 2010). The statement can be made that there is a positive relationship between automaticity and implicit knowledge. Therefore, the conclusion could be drawn that implicit knowledge indirectly improves situation awareness. Likewise, implicit knowledge is also related to the individual factor long-term memory stores. According to Endsley (1995b) we retrieve information from our long-term memory to make decisions and complete tasks successfully. Not all of this knowledge will be explicit, and some knowledge that was originally explicit can become implicit over time (R. Ellis, 2004; Hélie & Sun, 2010; Segalowitz, 2003; Sun et al., 2001). As a result, the long-term memories that are accessed to perform a task could largely consist of implicit knowledge. For this study the model of Endsley (1995b) was slightly adjusted (see Figure 3) to incorporate implicit knowledge as another important individual factor. On the one hand, implicit knowledge interacts with other individual factors, on the other hand, implicit knowledge also affects decision making and overall performance.

Figure 3

Adapted Endsley's Model of Situation Awareness including Implicit Knowledge



Note. The tile 'Implicit Knowledge' was added to this model, for the original model see Figure 1 or consult Endsley (1995b, p. 35).

2.2.6. Influence of Implicit Knowledge on the Situation Awareness of Roller Operators

Z. Zhang et al. (2023) concluded that various important cognitive concepts within the construction industry increase or decrease situation awareness (e.g., mental load, physical workload, hazard recognition). One of those concepts is implicit knowledge, upon which experienced roller operators rely heavily to achieve high-quality results (Makarov et al., 2023). The effects of various cognitive concepts that impact the situation awareness of roller operators have not been researched yet. As a result, this study investigated the impact of implicit knowledge on the situation awareness of roller operators. Prior research by Hasanzadeh et al. (2017) already established that implicit safety knowledge of construction sites improves situation awareness towards hazards. Therefore, it was hypothesized that implicit knowledge of asphalt compaction could improve the situation awareness of roller operators. Implicit knowledge is an important cognitive concept within the asphalt construction industry (Bijleveld & Dorée, 2014; Makarov et al., 2023) as current traditional working practices force roller operators to draw upon their inherent skills and past working experiences to achieve desired results (Bijleveld & Dorée, 2014; Makarov et al., 2023). Key quality parameters (e.g. the decrease in temperature of the asphalt mixture (Miller et al., 2011)) are simply not available to most roller operators (Bijleveld & Dorée, 2014). As a result, they have to make estimates (e.g. about the temperature of the asphalt) based on the experience they have, the quality of the communication within the team, and their situation awareness. Because of this roller operators learn individually and implicitly through time, which leads to quality variability in the long run (Bijleveld, Miller, & Dorée, 2015). That is why inexperienced roller operators do not possess much implicit knowledge yet, as this type of knowledge has to be acquired over time (Bijleveld & Dorée, 2014). In summary, much of the knowledge that roller operators possess will most likely be implicit and this knowledge will support their situation awareness.

2.3. Virtual Reality

This chapter discusses the use of Virtual Reality (VR) within the construction industry and the use of VR for measuring situation awareness. Furthermore, the advantages and limitations of simulations are shortly discussed and the importance of immersion is assessed as well.

2.3.1. Virtual Reality in the Construction Industry

Virtual Reality (VR) was initially marketed towards the gaming community but it has found its way to a wide variety of fields (Hamad & Jia, 2022). VR is especially useful for training, as real-world limitations don’t apply (Xie et al., 2021). For instance, participants can be trained or studied in a safe environment without being exposed to actually dangerous situations. Construction workers often find themselves in dangerous situations where minor mistakes can have grave consequences (Albert & Hallowell, 2012; Hasanzadeh et al., 2018; Kim et al., 2022). As a result, VR has received a great amount of attention from the construction industry (X. Li et al., 2018). Within a VR environment mistakes are never lethal, no materials go wasted and trainees can familiarize themselves with the workplace environment. Multiple VR environments have been developed with this in mind over the past twenty years. These VR environments are very distinct, they can simulate work zone inspections (Aati et al., 2020), stone cladding (Sacks et al., 2012), or the operation of mobile cranes for example (Fang et al., 2018). It is safe to say that VR has become a popular training method in the construction industry.

Research also indicates that VR training is often more effective at training professional skills than traditional methods (De Lorenzis et al., 2023; Han et al., 2022). Operators who had to deconstruct tower cranes for example learned better in a specialized VR environment, as opposed to other trainees that used traditional methods (H. Li et al., 2012). VR can also be used to train situation awareness. In the study of Nazir et al. (2015) industrial operators maintained better situation awareness after being trained with the help of a virtual 3D environment.

2.3.2. Researching Situation Awareness with Virtual Reality

Researchers often use VR within the construction industry to measure or train the situation awareness of participants (Choi et al., 2020; Han et al., 2022). Within VR simulated environments can be manipulated and the situation awareness of participants can be measured without interference (Choi et al., 2020). Furthermore, the experiences of participants become comparable as each participant witnessed the same situation, without any influence from the outside environment (Endsley, 1995a). Another advantage of simulations is the possibility to record the performance of a participant within the simulation. The recordings can subsequently be shown to participants as stimuli (Barton, 2015) to understand their thought processes.

A potential limitation of simulations, however, is sometimes the visual quality of simulated environments, as this affects the immersion and situation awareness of participants. Hébert-Lavoie et al. (2024) adjusted and manipulated the graphical quality of their VR environment (e.g. reducing the field of view) during their research. They found that when these graphical changes negatively influenced the immersion of participants, their SAGAT scores were affected as well. Cross et al. (2023) also found a positive relationship between immersion and situation awareness. The high resolution of their head-mounted display (HMD) and the quality of the user interface contributed to the immersion of the participants. This seems to confirm the notion that graphical quality (e.g. resolution, interface quality, field of view, etc.) impacts the immersion of participants in VR. Consequently, immersion seems to impact situation awareness as it ‘transports’ participants from the real world to a virtual setting, allowing them to be (more) aware within the virtual environment (Cross et al., 2023).

As immersion impacts situation awareness, various measures should be taken to ensure that participants remain immersed throughout the research. Firstly, participants that experience a VR environment with a head-mounted display (HMD) are more likely to be immersed (Servotte et al., 2020). Studies that compared conventional monitors, cylindrical simulation displays, and HMDs found that participants felt more immersed wearing an HMD (Clifford et al., 2020; Shu et al., 2018). This makes sense as high-quality HMDs can show realistic virtual environments at high frame rates (Servotte et al., 2020). Secondly, Witmer and Singer (1998) and Cross et al. (2023) found that control strongly affects immersion as well. When a participant has more control they engage more actively with the virtual environment that surrounds them. In a study from Clifford et al. (2018) participants expressed a desire for more control, so they could feel more present within the system. There are, of course, more factors that influence immersion. A good pre-briefing, for example, helps to set the narrative for the participant (Servotte et al., 2020), which causes participants to be more immersed within the VR environment as they grasp the narrative, their purpose, and the goals of the simulation.

3. Current Study

The theoretical framework established that situation awareness is important for roller operators within the asphalt construction industry (Bijleveld & Dorée, 2014). It is clear that roller operators need good situation awareness (Makarov et al., 2023), but which individual factors (Endsley, 1995b) contribute to good situation awareness within this particular field, remains undocumented. Based on the literature that was found the decision was made to focus on implicit knowledge as a potential factor that positively influences the situation awareness of experienced roller operators. As it is difficult to verbalize implicit knowledge various elicitation techniques (Barton, 2015) and cues (Mancy & Reid, 2006) for implicit knowledge were studied. Furthermore, research from various fields confirms that there is usually a positive relationship between experience and situation awareness. As this relationship has not been studied yet within this particular context the potential differences in situation awareness between the experienced and inexperienced participants were assessed as well (Cak et al., 2020; Carretta et al., 1996; Endsley, 2006). To investigate the relationship between implicit knowledge and situation awareness the following research question was formulated: "*How does the situation awareness of experienced roller operators differ from those of inexperienced operators, and what role does implicit knowledge play in this difference?*". Based on this research question (and the theoretical framework) the following hypothesis was formulated as well: "*The experienced roller operators will have better situation awareness due to the implicit knowledge that they possess.*". To structure the research and answer the above research question, the following sub-questions were formulated:

- How do the scores for each level of situation awareness vary between the inexperienced and the experienced roller operators?
- To what extent can experienced and inexperienced roller operators verbalize the knowledge they use to make decisions?

Additionally, the following hypotheses were formulated for these sub-questions in the theoretical framework:

- The experienced roller operators will have better situation awareness, their overall score and the scores for each individual level will be higher.
- The experienced roller operators will struggle to verbalize their decision making (knowledge) due to their reliance on implicit knowledge.

4. Research Design and Method

4.1. Research Design & Participants

A cross-sectional mixed method design was used to examine the potential differences in situation awareness and the influence of implicit knowledge on experienced and inexperienced roller operators. The Dutch construction companies Heijmans and Gebr. Van Kessel were contacted to participate. Moreover, nearby vocational students of road construction from the ‘Stichting tot Opleidingen van Machinisten voor Aannemersbedrijven’ (SOMA) were contacted to participate as well. Convenience sampling was applied since the study needed participants who were available, easy to access, and willing to participate in the research. A major difference between these two groups was the amount of time each participant spent on a roller. Operating a roller, however, is not the only task most roller operators perform; some will have other responsibilities as well. This inconsistency in weekly and yearly hours made it difficult for the experienced participants to estimate the amount of time they already spent on a roller. Therefore, the decision was made to measure experience by the number of years each participant worked on a roller. The experienced roller operators had 10 to 32 years of experience ($M = 20.75$, $SD = 8.89$). The inexperienced group had 25 hours of experience, except for one participant with 100 hours. To confirm that the means of both groups were significantly different a Mann-Whitney U Test was performed. The test confirmed that the means of both groups were significantly different. This is logical given the fact that everyone in the inexperienced group only had one year of experience and the other group had an average experience of 20 years. It is also important to highlight the age gap between both groups. The average age within the experienced group was 45 years, which was substantially higher than the average age of 18 within the inexperienced group. Furthermore, it must be noted that the majority of the participants in both groups were male.

From both groups every participant was asked to participate in the stimulated recall interviews as well. According to Guest et al. (2006) and Coenen et al. (2011) no new information is usually observed in the data after the first 12 interviews. The sample of inexperienced roller operators was quite homogeneous, data saturation was achieved as early as six interviews. For the experienced sample data saturation was achieved around eight interviews, as the experienced participants had far more thoughts and insights to share on their experience during the interviews. Every participant was willing to participate in the interviews, one participant however was unwilling to participate in the research if they had to control the virtual roller within the virtual 3D environment. As the sample size was already quite slim, this participant and another, who experienced immediate nausea, were both allowed to operate the roller without the head-mounted display; they viewed the virtual environment on the laptop screen.

4.2. Instruments

4.2.1. SAGAT Questionnaire

Various instruments can be used to measure situation awareness in virtual 3D environments. Salmon et al. (2006) constructed a list of the most well-known measurement techniques. For this study the decision was made to use SAGAT, the Situation-Awareness-Global-Assessment-Technique (Endsley, 1995a). SAGAT consists of multiple queries which evaluate the situation awareness of a participant (Endsley, 1988). These queries assess whether a participant was aware of certain (important) elements within their environment. It must be noted however that SAGAT is an explicit measure of situation awareness (Banbury et al., 2000), this measurement technique can only measure what a participant was consciously aware of (Gugerty & Falzetta, 2005). SAGAT cannot measure any implicit attentional processes (Gugerty & Falzetta, 2005), as these are usually unavailable to conscious thought or verbal description (Banbury et al., 2000). SAGAT can be used in various domains, but the queries have to be customized (Endsley et al., 1998). Queries that are presented to pilots (Endsley, 1995a) are therefore different from the queries that are presented to forklift operators (Choi et al., 2020) for example. The purpose of the queries remains the same however, they asses one's knowledge of what is happening around them. All the queries together should cover each level of situation awareness from Endsley's (1995b) model (see Figure 1). To summarize, the goal of the queries is to question the perception, comprehension, and projection of each participant.

Among the various techniques that can be used to measure situation awareness, SAGAT was chosen for several reasons. Firstly, most measurement techniques of situation awareness have not been validated properly, (Salmon et al. 2006), but numerous studies do confirm the validity of SAGAT (Jones & Kaber, 2004). Secondly, both SAGAT and the Situational Awareness Rating Technique (SART), (Taylor, 2011) are used frequently to measure situation awareness according to Salmon et al. (2006). However, multiple researchers compared SAGAT and SART and found that SAGAT was more accurate at measuring the situation awareness of their participants (Endsley et al., 1998; Salmon et al., 2009). It must be noted as well that SART is a subjective measure of situation awareness, whereas SAGAT is an objective measure. Therefore, SART has various limitations (e.g. the inability of operators to rate their own situation awareness) according to Endsley et al. (1998). Thirdly, there is a noticeable trend in the use of SAGAT in road transportation research to measure situation awareness (Salmon et al., 2012). Recent research by Choi et al. (2020) also used SAGAT to measure the situation awareness of their participants who drove a forklift. Some researchers did not use SAGAT in their road transportation research but their methods were still noticeably similar (Gugerty, 1997; Kass et al., 2007).

In this study participants had to answer four multiple-choice questions for each level of situation awareness: perception, comprehension, and projection. Perception questions measured how aware each participant was of certain elements within their environment (e.g. “Which side of the asphalt is the low side?”). Comprehension questions assessed whether participants understood the meaning and significance of the elements they perceived (e.g. “Which compacting phase are you currently in?”). Lastly, projection questions investigated the ability of each participant to anticipate future events (e.g. “How many more times should the indicated area be compacted to reach the correct level of compaction?”). These questions were designed as multiple-choice questions with up to four answer options per question. The participants received these questions at the end of the simulation, so their situation awareness could be assessed. It is important to note that the participants lost access to the virtual environment as soon as the questionnaire began. As a result, they could not look around in the environment and search for potential clues to answer the questions from the questionnaire. Each question was written in Dutch since the study was conducted in the Netherlands and every participant spoke Dutch. Appendix A provides an overview of all the questions that were part of the SAGAT questionnaire. A point was awarded for every correct answer which made the measurement level of this variable interval. It must be noted however that it is not true that participants who obtained zero points possess no situation awareness at all. Similarly, participants who obtained 12 points are most likely not aware all the time.

4.2.2. Stimulated Recall Interviews

Research confirms that it can be challenging to reveal implicit knowledge (Bijleveld & Dorée, 2014; L. Zhang et al., 2013). To handle this challenge this study used stimulated recall interviews to assess the decision-making process of its participants. A stimulated recall interview is considered an elicitation technique (Barton, 2015) which is particularly suitable for eliciting implicit knowledge (Van Braak et al., 2018). During such an interview stimuli (e.g. video material) are used to reveal the thoughts of a participant that would not be articulated under normal circumstances (Barton, 2015). This is why stimulated recall interviews are suitable for discovering and investigating cognitive processes (Lyle, 2003).

Participants were shown video clips of their performance within the virtual 3D environment (more information about these video clips can be found in Chapter 4.3.3.) The performance of each roller operator was automatically recorded so it could be shown almost immediately to a participant. This is important as minimizing the time delay between the virtual reality experience and the interview increases the validity of this approach (Lyle, 2003). Another point to consider is the fact that semi-structured stimulated recall interviews generate richer data compared to low-structured, participant-led interviews (Paskins et al., 2014). As a result, this study followed the recommendations of Van Braak et al. (2018) to prepare a set of neutral, open-ended questions (e.g. “What is happening here?”) to elicit as much implicit knowledge from participants as possible. Additionally, responses of participants were often met with follow-up questions (e.g. “Why did you change your speed?”) to encourage them to think deeply about the decisions they made. An overview of the type of questions that were asked can be found in Appendix B. Some participants occasionally gave very short responses to certain questions, in line with the recommendations from Babbie et al. (2020) various probing techniques were employed to gather sufficient information from each participant. An example of one such probing technique is silence, which occasionally led to participants filling the void with additional commentary.

O’Brien (1993) also formulated a list of guidelines for conducting stimulated recall interviews, but these guidelines were mostly written for unstructured, participant-led interviews. The recommendations from O’Brien (1993) that were relevant (e.g. avoid leading questions) were taken into account. Furthermore, O’Brien (1993) also states that participants need to be made aware of the fact that there are no right or wrong answers. This was explained before every interview, and as a result participants did not feel the need to produce explanations to defend the actions they took. Whilst the guidelines of O’Brien (1993) and Van Braak et al. (2018) focus on stimulated recall interviews, general recommendations for interviewing from Babbie (2020) were also taken into account. In terms of appearance, the researcher dressed similarly to the participants who were interviewed. To blend in and make participants feel more comfortable. Furthermore, the researcher remained relaxed and friendly during the interviews, displaying a pleasant demeanor towards each participant.

The questions participants received during the stimulated recall interviews addressed the various decisions that the participants had to make. The responses of the participants were later on analyzed to determine if the knowledge they communicated was implicit or explicit. Based on the existing theory of Mancy and Reid (2006) and Ambrosini and Bowman (2001) an initial codebook was developed. During the analysis more codes were created as more concepts, thoughts, and themes were exposed from the transcripts. The initial codebook that was constructed before the interviews can be seen in Table 1 with actual examples from the interviews. Some examples are empty (e.g. ‘…’) as those signs of implicit knowledge were not encountered during the actual interviews.

Near the end of every interview each participant was also asked if there were any questions in particular that really made them think about the decisions they took. The goal of this question was to establish if there were any questions during the interview that were especially successful at getting participants to communicate knowledge that they would not divulge under normal circumstances. Based on the responses from the participants no adjustments were made to the interviews as most participants stated that they found every question reasonably easy to answer. None of the participants experienced the interviews as particularly challenging or difficult.

Table 1

Initial Codebook for the Stimulated Recall Interviews

Code Name	Definition	Real Example
Signs of Implicit Knowledge		
Unaware of Knowledge	The participant is not aware how or why they used a certain skill. In other words, the participant claims not to know how success was achieved.	"…"
Struggling to Articulate Knowledge	The participant struggles to articulate their knowledge, they may state that they find it difficult to explain themselves for example. Note: This must not be confused with a lack of knowledge.	P18: "Well, uh yes... that is difficult [to explain]. Well it is hard to express as this is something that you learn through time, because well... you can..., you cannot follow the [paving] machine right now, your roller passes will be way too short."
Reliance on Concrete Examples	The participant explains their knowledge through examples, they rely on practical examples to get their point across.	P12: "Well, alright, it's uhm... look if I... it depends on the weather you know, and whether it's a top layer... or whether I have to immediately be there because the layer is quite thin for example."
Descriptive Language	The participant vaguely explains their knowledge, using vague terminology like "something like that". It's clear the participant knows more, but the participant sticks to vague terminology.	"…"
Surprised Understanding	The participant becomes aware of knowledge they possess (they may even act surprised), implicit knowledge is suddenly made explicit (to a certain degree).	P18: "Well, I never really thought about it haha."
Use of Metaphors	The participant uses a metaphor to communicate their knowledge (e.g. to explain their reasoning or their goals). However, the participant is able to explain how and why they used the skill afterwards.	"…"

4.3. Procedure

4.3.1. At the Start

A few steps were taken before the participants were able to use the virtual 3D environment or participate in the interviews. First and foremost, each participant had to physically sign an informed consent form, which can be found in Appendix C, before they were able to begin. Subsequently, an online questionnaire was administered to capture the demographics of each participant. This questionnaire contained questions about the age, gender, and level of education of each participant. This questionnaire was administered via a laptop with Microsoft Forms, the questions which were in the form can be found in Appendix D. Furthermore, each participant also had to answer questions about the amount of time that they spent on a roller (e.g. “How many years have you worked with a roller?”). To be precise, participants were also asked how many hours they, on average, spent on a roller each week. These questions were not part of the Microsoft Form, instead, they were asked by the researcher to ensure the working experience of each participant was cataloged correctly. Lastly, participants received instructions about the task at hand, what to expect, and how everything works. A detailed overview of the instructions that were provided at this stage of the research can be found in Appendix E.

4.3.2. The Virtual 3D Environment

A virtual 3D environment was used to imitate the task of asphalt compaction. Participants used a steering wheel and joystick to operate a virtual roller, additionally, they wore head-mounted displays for immersion (Servotte et al., 2020). The joystick and steering wheel were connected to a laptop and allowed the participants to steer the roller in any desired direction. Before any participant was able to control the roller they first had to click through a ‘welcome page’ and a ‘virtual meeting page’. These pages gave information about the task at hand and the purpose of the research. Therefore, participants knew what type of asphalt they were going to use, what type of road they would be paving, and what the expected weather conditions would be like. This pre-briefing set the narrative for each participant, so they would feel more immersed in the environment (Servotte et al., 2020). After the pre-briefing participants were shown a short tutorial that explained how the steering wheel and joystick worked. In some cases the information in the pre-briefing and the tutorials led to questions, an overview of various common questions and the correct responses can be found in Appendix F. After participants clicked through the tutorial they were able to put the headset on and start the simulation (see Figure 4).

Figure 4

Picture of an Experienced Participant who is Operating the Virtual Roller

Within the virtual 3D environment participants had to follow a paving machine to compact a newly paved straight road (see Figure 5). Every participant had to make various decisions on their own. For example: How do I compact this stretch of road for the best result? Each participant was able to approach this task differently, as a result, each participant had to make their own decisions. Some participants waited quite a while before they started compacting the asphalt whilst others immediately placed their roller on the small stretch of available asphalt. Some started on the left side of the road, others on the right and a select few began in the middle. To make the virtual 3D environment more challenging the weather changed after four minutes from cloudy to rainy, affecting the temperature. Participants had to notice this as well to make quick decisions and properly pave the road under changing circumstances. During the simulation the researcher was constantly present to solve technical issues. Regular questions (e.g. “How should I pave the left part of the road?”) were often not answered as it was important for the research that participants relied on their own knowledge of asphalt compaction during the simulation. Therefore, questions were often met with polite deflection (e.g. “Great question, unfortunately, I cannot tell you what approach is best here!”). In the simulation participants were on a self-guided journey, where the researcher mainly acted as the facilitator of the virtual environment. In reality, most participants did not ask questions, but instead, they shared thoughts that crossed their minds whilst they were operating the virtual roller (e.g. “Hey, it is starting to rain!” or “The roller feels a little slow?”). The complete simulation lasted eight minutes, after this period had gone by the simulation automatically ended. After the participants were done working in the virtual 3D environment, they were confronted with multiple-choice questions that assessed their situation awareness. To answer these questions participants did not need to wear the headset.

Figure 5

2D Screenshot of the Virtual Environment

4.3.3. The Stimulated Recall Interviews

During the stimulated recall interviews participants watched a recording of their behavior within the virtual 3D environment. Parts of these recordings were very similar for every participant, as they all encountered the same weather change for example. The weather consistently changed from cloudy to rainy for every participant after four minutes. As a result, all participants watched a similar video clip of how they handled this change, showcasing the decisions they made. The rest of the recording was of course different for every participant. Whilst watching the recording participants received various open-ended questions regarding their decision making. An overview of the two most essential moments that participants saw in the recording can be seen in Table 2. The participants were able to pause and replay the video clips of their own accord. This was meant to stimulate the thought processes of the participants as they needed to answer various neutral open-ended questions. In reality, most participants did not touch the laptop at all to pause or replay the recording. Additionally, participants were given some breathing room at the start of the interview to share their thoughts and impressions about the simulation. As some participants had strong opinions about the simulation they were able to share these right at the start. As a result, these participants were more likely to focus on the questions of the interviewer than any potential thoughts or opinions that they had not shared yet. After the interview participants received a short debriefing where they could ask any remaining questions, inquire about the purpose of the study, or share their experience. A QR code with the contact information of the researcher was shown as well (see Appendix G). As a result, each participant was still able to contact the researcher after the study concluded.

Table 2

Recordings of Participant Behaviour Within the Virtual 3D Environment

Recording	Description	Example Question
Start of the Simulation	At the start of the simulation, the participant has to decide how to approach the compaction task at hand.	"You started on the right side of the road?"
Weather Change	During the simulation the weather changes. The participant needs to decide how to move forward now that the temperature is dropping.	"Why did you alter the speed of the roller here?"
Rest of the Recording (different for each participant)	During the simulation various participants will make unique decisions that can be analyzed during the interview.	"What was your intention here, changing direction so suddenly?"

4.3.4. Ethical Considerations

All participants signed an informed consent form before they participated in the study. Participation was completely voluntary and there were no incentives from the University of Twente for participating. Each participant was however given a canned sugary drink and a snack (e.g. Twix) to reward their willingness to cooperate in the research! Before any actual data was collected the Ethical Committee of the University of Twente was consulted and approval was obtained (request 231467). Each participant also received the possibility to provide their email address in the Microsoft Form if they were interested in the results of the study. Finally, participants were told to immediately notify the researcher and take the head-mounted display off, if they experienced any form of motion sickness. Possible symptoms include nausea, dizziness, and cold sweats (Chattha et al., 2020). Two participants experienced some of these symptoms and they were immediately encouraged to step outside for some fresh air and natural light. Within a few minutes, these participants regained their footing. Of course, any affected participants were not permitted to finish the simulation, although one nauseous participant came back later to try the simulation again without the head-mounted display. One participant became slightly nauseous after the interview, even though they felt fine during the simulation. This participant took a small break afterwards and was given an additional sugary drink in the hopes that they would feel better rather sooner than later.

For the online questionnaire Microsoft Forms was used as it met every important privacy regulation. After the data collection the data was moved from Microsoft Forms to an Excel spreadsheet which was saved in the university's OneDrive of the researcher. The recordings of the participants, within the virtual 3D environment and the interviews were anonymized as each participant received a number (e.g. ‘P14’, in other words, ‘participant 14’). The audio and video files of each participant were also saved in the University’s OneDrive of the researcher. Finally, a password-protected ‘Participant ID log’ (SPSS Data Set) was also saved in the University’s OneDrive to maintain the link between all the data and the various individuals who participated in the study. In the end, every piece of data that was collected was handed over to the supervisor of the study.

4.4. Data Analysis

4.4.1. Quantitative Data Analysis

Every participant had their situation awareness measured with SAGAT (Endsley, 1995a) within the virtual 3D environment. The software was able to evaluate ten questions automatically, questions one and eleven were manually assessed by the researcher (see Appendix A). The unit of analysis was the situation awareness score of each participant. The statistical software package SPSS was used to analyze the data. The means of the scores for each level of situation awareness were calculated for both groups of roller operators. The sample size was too small to perform a *t* test as adequate power could not be maintained with eleven participants in the inexperienced group and eight participants in the experienced group (Wilson VanVoorhis & Morgan, 2007). To compare the scores between the inexperienced and experienced participants the non-parametric Mann-Whitney *U* Test was performed. The participants of each group were not completely homogeneous with one another as they varied in experience, age, and situation awareness scores, for example. Therefore, an exploratory data analysis was conducted as well, to learn more about each group and to see if there were any notable differences within each group.

4.4.2. Qualitative Data Analysis

The behavior of each roller operator within the virtual 3D environment was recorded. The participants were aware of this as they signed an informed consent form beforehand. These recordings were used during the stimulated recall interviews. The audio of the stimulated recall interviews was recorded and transcribed automatically with Amberscript. This software was chosen in particular as it met every important privacy regulation. To ensure the transcripts were correct they were also checked by hand. AtlasTI was used to code the transcripts and analyze the results. The analysis started deductively with a small set of codes (see Table 1) based on the cues that were developed by Mancy and Reid (2006) and Ambrosini and Bowman (2001). During the thematic analysis of the interviews numerous additional codes were created as the initial set only covered signs for implicit knowledge. As more and more data were analyzed, additional codes were created and iterated upon. This was a process of open coding (Babbie, 2020) to learn more from the data and expose all the concepts and thoughts within the transcripts. To properly categorize all the information every transcript was checked multiple times, the final codebook can be found in Appendix I. The intercoder reliability (ICR) of the codebook was assessed as well to ensure that the codebook was accurate and reliable. Throughout this process, the researcher collaborated with another EST student, consistently applying the practical guidelines from O'Connor and Joffe (2020). The ICR was calculated with AtlasTI by using the statistical test Krippendorff's α (Hayes & Krippendorff, 2007). A formal statistical test was used to calculate the ICR, as basic percentage agreements are often regarded as inadequate indexes by statisticians (Feng, 2014). Initially, the outcome of Krippendorff's α statistical test produced an insufficient result of 0.637. By improving the descriptions of various codes the result of Krippendorff's α statistical test improved to 0.839. Which is a good indication that there was a satisfactory level of agreement between both coders (Marzi et al., 2024).

5. Results

5.1. Quantitative Analysis and Results

The purpose of the quantitative analysis was to analyze the results of the situation awareness questionnaire. The average scores for the overall questionnaire and the individual levels (e.g. perception) were calculated and the scores of both groups were visualized with histograms in SPSS (see Appendix H). Significant differences were assessed with non-parametric tests, as the sample size was too small to perform *t* tests. Adequate power could not be maintained with eleven participants in the inexperienced group and eight participants in the experienced group (Wilson VanVoorhis & Morgan, 2007). The goal of the quantitative analysis was to assess if the situation awareness scores differed significantly between experienced and inexperienced roller operators. The qualitative analysis, on the other hand, concentrated on exploring the explicit and implicit knowledge that roller operators communicated during the interviews, to answer the remaining research questions.

5.1.1. Exploratory Data Analysis

An exploratory data analysis was conducted on the demographic information that was collected by the online questionnaire. This analysis did not provide many additional insights aside from the fact that the younger inexperienced group had more experience with gaming. Of the eleven inexperienced participants, six regularly played video games in comparison to the experienced group where five of the nine participants never played a video game in their life. This was evidenced by the fact that some experienced participants became (slightly) nauseous from the environment and many of them were not afraid to communicate their unfamiliarity with the controllers or the HMD. The experienced participants who actively struggled with the controls never played a video game in their lives. The participants of the inexperienced group found it much easier to control the roller which may be explained by their familiarity with virtual environments, computers, and gaming in general. The above illustrates that there is nothing inherently wrong with the controls of the roller or the HMD; the ease of use depends on the participant.

5.1.2. Situation Awareness Questionnaire

The twelve questions of the situation awareness questionnaire were designed to measure the situation awareness of each participant. Two questions were not taken into account when these results were calculated. Question two (“Which side of the asphalt is the low side?”) could not be answered based on the visuals of the simulation alone (see Figure 5). There were no visible height differences in the virtual asphalt. As a result, the only participants who were able to answer this question correctly were the participants who remembered this information from the ‘virtual meeting page’ (see Chapter 4.3.2.). Some participants missed this information, others forgot the information and some outright guessed the right answer. When working with an actual roller, roller operators can tell what the ‘low side’ of the asphalt is by simply looking at the asphalt. Inexperienced participant P07 said during their interview: “*You don’t really see any height differences and you can’t see the camber of the road. That the left is the lowest point and the right is the highest point… uhmm, well you don’t see that difference either!*”. This question was therefore excluded from the data analysis as this information could not be retrieved from the virtual environment.

For similar reasons, question eight (“Can you turn on the vibration function now?”) was excluded from the data analysis as well. The vibration functionality should not be used on pervious concrete (which is a specific type of asphalt). Experienced participant P19 explained this through an example during the interview: “*No, you don’t vibrate on pervious concrete, as it is just a mix of rocks and if you start vibrating, well… compare it to hitting a rock with a hammer, you’ll split it straight down the middle!”*. The ‘rocks’ that P19 refers to need to remain intact as they form the skeleton of the pervious concrete; they are essential for the structural integrity of asphalt (Sičáková & Kováč, 2020). As the participants were unable to visually identify the asphalt this information could only be obtained from the ‘virtual meeting page’. This question was therefore excluded from the data analysis as well, as the correct answer to this question could not be retrieved from the virtual environment.

5.1.3. Questionnaire Score Analysis

The answers to the ten questions that remained were subsequently analyzed and the results can be found in Table 3. The table contains medians and standard deviations for each level of situation awareness (e.g. perception) and the total score. Medians are a more appropriate statistic for non-parametric tests than means (Field, 2018). The table also shows the results of the Mann-Whitney *U* Test that was conducted, to assess if the experienced participants scored significantly higher. The assumptions[1] for this test were met as the data from both groups was independent of one another and the measurement level of the data was interval (Field, 2018). The distribution of the data was assessed as well, additional histograms were created with SPSS, which can be found in Appendix H. The exact significance *p*-value was used instead of the asymptotic method which produces more accurate results for samples with less than fifty participants (Field, 2018). Furthermore, the effect size was calculated by hand with the formula: $r = \frac{z}{\sqrt{N}}$.

[1] Various statistical blogs (Bobbitt, 2018) also state that the distribution of the data should be roughly the same. This assumption is however not mentioned by Field (2018) or Milenović (2011), who states that the Mann-Whitney test can even be performed if the distribution of the data is unknown. This assumption was therefore not taken into account.

Table 3

Differences in Situation Awareness Scores

Situation Awareness	Median Score (SD)		*U*	*p*	*r*
	Inexp.	Exp.			
Perception	66.67 (22.47)	83.33 (17.82)	48.000	.778	0.085
Comprehension	66.67 (25.03)	100.00 (0.00)	80.000	.002*	0.749
Projection	75.00 (28.41)	75.00 (12.94)	52.000	.545	0.165
Total Score	70.00 (16.40)	90.00 (3.54)	74.500	.009*	0.604

Note. ‘Inexp.’ are inexperienced participants and ‘Exp.’ are experienced participants.
$p < .05$.

For this study, it was hypothesized that experienced roller operators would have better situation awareness than their inexperienced counterparts. This was indeed the case for the total score of the questionnaire. Experienced roller operators (*Mdn* = 90.00) scored significantly higher than the inexperienced roller operators (*Mdn* = 70.00), $U = 74.50$, $z = 2.632$, $p = 0.009$, $r = 0.6038$. The effect size is large, as it is greater than 0.5, which indicates that the difference between both groups is quite substantial (Field, 2018). In other words, if you were to pick one roller operator from each group, the experienced roller operator would most likely have a higher score. When the scores are separated in their respective levels (e.g. perception) the difference is less pronounced. Surprisingly, no significant difference was found between both groups for the levels perception and projection. The experienced roller operators (*Mdn* = 83.33) did not score significantly higher than the inexperienced roller operators (*Mdn* = 66.67) for the level perception, $U = 48.00$, $z = 0.372$, $p = 0.778$, $r = 0.0853$. The effect size is considered small, as it is below 0.3. This would indicate that the experienced roller operators were not significantly better at perceiving (important) elements in the virtual environment. Similarly, for the level projection, the experienced operators (*Mdn* = 75.00) also did not score significantly higher than the inexperienced operators (*Mdn* = 75.00), $U = 52.00$, $z = 0.719$, $p = 0.545$, $r = 0.1649$. The effect size is small for this level as well. As a result, experienced roller operators are not significantly better at predicting what will happen to some of these elements in the near future. A significant difference was however found for the questions that were related to the level comprehension. Contrary to expectations, every participant within the experienced group (*Mdn* = 100.00) answered these questions correctly. Their scores were significantly higher than the scores of the inexperienced participants (*Mdn* = 66.67), $U = 80.00$, $z = 3.2652$, $p = 0.002$, $r = 0.7490$. As expected, the effect size is therefore large for this level as well. This would indicate that experienced roller operators are far better at considering the importance and relevance of elements within their environment.

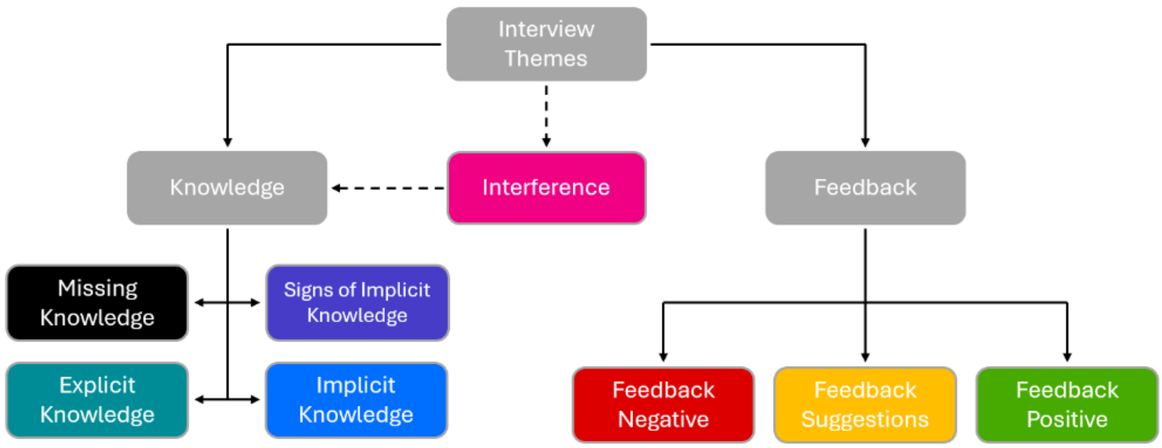
In summary, it was hypothesized for this study that experienced roller operators would have better situation awareness than their inexperienced counterparts. This hypothesis turned out to be true for the overall score and the level comprehension, as opposed to the levels perception and projection where the hypothesis was rejected. These results paint a complicated picture where experienced roller operators are considerably better at comprehending relevant and important elements from their environment, but they are only scarcely better at projecting how these elements will change in the near future. These results will be discussed further in the discussion section as the exploratory data analysis and the qualitative analysis are covered first.

5.2. Qualitative Analysis and Results

The coding process revealed that two overarching themes covered seven of the eight codes that were developed in AtlasTI. Almost every code that was applied to the transcripts revolved around either knowledge or feedback. Every piece of knowledge that was communicated was coded as the study was mainly looking for implicit and explicit knowledge. Furthermore, many participants, especially the experienced participants, gave a lot of feedback which was often negative. This feedback was coded as well as it indicates how participants experienced the simulation. In some cases participants made suggestions that could be taken into account to improve various aspects of the simulation. After the coding process concluded a ‘code tree’ was constructed (see Figure 6) that illustrates how the codes were grouped and color-coded within AtlasTI. The final codebook can be found in Appendix I.

Figure 6

Thematic Code Tree of all the Transcripts



For this study, it was hypothesized that experienced roller operators would struggle to verbalize their decision making (knowledge) due to their reliance on implicit knowledge. Additionally, it was also hypothesized that the presence of implicit knowledge would improve the situation awareness of the experienced roller operators. In reality, the coding process revealed that most experienced participants were able to articulate their knowledge quite well. Very little knowledge that was revealed through the stimulated recall interviews turned out to be implicit. The next paragraphs will cover various situations during the simulation where participants used explicit and implicit knowledge to perform their jobs. Note that participants who are mentioned throughout these paragraphs will be addressed with they/their pronouns to preserve their anonymity. Initially, the start of the simulation is discussed where roller operators had to decide how to start. Subsequently, the change in weather is discussed, and how roller operators handled this change. Then, some noticeable differences between both groups are covered (e.g. water management) and the specific signs of implicit knowledge that were found by Mancy and Reid (2006) are addressed as well. Finally, the most essential feedback and suggestions that various participants gave are shortly illustrated too, and a conclusion is drawn.

5.2.1. The Start of the Simulation

This section outlines how experienced and inexperienced participants approached the start of the simulation. Firstly, the approach of the experienced participants is described by analyzing various statements from the interviews. Subsequently, the approach of the inexperienced participants is assessed as well. The knowledge that the participants communicated during the interviews is categorized too, as a few experienced participants did exhibit some signs of implicit knowledge. At the start of the simulation every participant had to make two important decisions, when do I start and where do I start? There was no asphalt at the start of the simulation as the paving process starts when the simulation begins. As a result, participants saw very little asphalt when they began the simulation (see Figure 7).

Figure 7

2D Screenshot Taken During the Start of the Simulation

5.2.1.1. The Approach of the Experienced Participants. The experienced roller operators patiently waited at the start of the simulation. During the interview the researcher asked various participants why they decided to wait. Experienced participant P16 calmly explained why they took their time:

> *If you start driving now and you compact a meter you immediately create a stopping point. That doesn't work, especially since this is pervious concrete... if you are too close to the machine you'll close it [pervious concrete] up immediately, and with pervious concrete, well uhm... that shouldn't be the intention*.

Experienced participant P16 was able to articulate their knowledge quite well by projecting what would happen if they would not have waited at the start of the simulation. Their explanation contains two independent reasons for waiting at the start. Firstly, they did not want to stop their roller on the asphalt unnecessarily, as each stop would leave small imperfections behind (Hand et al., 2021). In other words, P16 wanted to make long roller passes, which means the paving machines need to be further away. Secondly, they also made this decision based on the type of asphalt that was used. They waited as they wanted to preserve the permeability of the concrete, making sure that water could still infiltrate its structure (Wei et al., 2022). During the interview, P16 communicated these explanations quite effortlessly and therefore it can be assumed that their knowledge on this topic was explicit. Experienced participant P13 did not mention the stopping points, but they did mention that the type of asphalt impacted their decision:

> *Well, you need to have the room to uhm…, to uhm… to to roll, to make your roller passes. And if you do small passes, you'll compact much more and with pervious concrete you are not supposed to compact it that much.*

The knowledge of participant P13 was explicit as well, as they were able to verbalize why they waited at the start of the simulation. Providing an explanation (like experienced participant P13 or P16) was not effortless for every participant. Experienced participant P18 waited approximately 2 minutes and 40 seconds before they moved the virtual roller into position. Upon questioning them about this decision they were slightly bewildered and their response contained a sign of implicit knowledge (Mancy & Reid, 2006):

> *Well, uh yes... that is difficult [to explain]. Well it is hard to express as this is something that you learn through time, because well... you can..., you cannot follow the [paving] machine right now, your roller passes will be way too short.*

Further questioning by the researcher revealed that experienced participant P18 wanted to avoid short roller passes as they would create far too many stopping points. It was quite challenging for P18 to explain their motivations and afterwards they admitted the following: "*Well, I never really thought about it haha.*" P18 was somewhat surprised about the reasoning behind their own decision, which would be classified by Mancy and Reid (2006) as a sign of implicit knowledge: the participant had a 'surprised understanding'. It is important to note that participant P18 had over thirty years of experience on a roller and it could well be that throughout the years some of the explicit knowledge they possessed became implicit. And as a result, it became more challenging for P18 to verbalize their reasoning (Hélie & Sun, 2010). Just like P18, experienced participant P12 showed various signs of implicit knowledge as well, as they formulated countless concrete examples of why they most likely decided to wait:

> *Well, alright, it's uhm... look if I... it depends on the weather you know, and whether it's a top layer... or whether I have to immediately be there because the layer is quite thin for example. Otherwise this is... this is... this is [pointing at the simulation] a base layer, so to speak, what I see here? I see a rubble track here and uhm... I don't want to create too many stopping points.*

Through various examples (there were more beyond this quote) participant P12 explained that a lot of factors impacted their decision to start (e.g. the condition of the weather, the type of asphalt, and the layer that they are working on). Ultimately, when the researcher asked if all these thoughts crossed their mind during the simulation, participant P12 hastily admitted that -in the moment- it came down to a ‘hunch’. In the words of P12: “*No, no-no-no-no... it’s a feeling!*” Although the knowledge of P12 on this topic was consciously accessible there was also a subconscious element, which they described as a ‘feeling’.

5.2.1.2. The Approach of the Inexperienced Participants. The inexperienced participants occasionally waited at the start of the simulation, but their reasoning was substantially different from the experienced participants. Inexperienced participant P05 confidently explained why they decided to wait:

> *Well, I first wanted to [wait until]… I mean when they [paving machines] are a few meters forward, otherwise you have very little room. And it doesn’t really work if you have to drive forwards and backwards all the time. So I waited until uhm… something [asphalt] was laid.*

Inexperienced participant P05 simply waited because they wanted more room to move the roller around, their reasoning is very practical and unrelated to the type of asphalt that is being used or the imperfections that rollers create when they stop too much (Hand et al., 2021). Quite similarly, inexperienced participant P04 gave the same reasoning:

> *I was getting my bearings and I was uhm… making sure that the paving machine was further ahead of me, so that I would have some length whilst rolling, so that you don’t have to keep driving forwards and backward on a tiny stretch [of asphalt]. So that you can really… so you can place the roller further away.*

Their explanations do not contain any reasoning beyond the fact that they need enough room to make long roller passes. As these inexperienced operators are still learning it can be assumed that they were probably taught to make long roller passes, but they may not remember the exact reason why these long passes are important. As a result, their comprehension of the situation is solely based on the space that the roller needs to operate. Other important elements like stopping points or the type of asphalt were not taken into account. It must be noted that some inexperienced participants did not perceive the small amount of asphalt at the start of the simulation as an issue. Some inexperienced participants did not wait at the start of the simulation as they started compacting the small stretch of available asphalt right away, inexperienced participant P02 explained their reasoning: “*Well, I wanted to see in the beginning well.... what would happen if I were to drive over the asphalt, if you can see it [change], or uhm...*”. This example illustrates a clear lack of knowledge, as participant P02 most likely did not know the negative consequences of making short roller passes on pervious concrete or compacting asphalt that is still too hot.

5.2.1.3. Summary. Almost every experienced participant was able to explain why they waited at the start of the simulation. And whilst this knowledge was somewhat implicit for a few experienced participants, they were still able to explain their reasoning to a certain degree. Ultimately, only experienced participant P12 admitted that it came down to a 'feeling' which made them decide that it was time to start. The experienced roller operators made an accurate projection of the future where starting too soon would harm the permeability of the concrete and cause unnecessary imperfections in the asphalt. The inexperienced participants possessed significantly less knowledge than their experienced counterparts. As a result, the projections they made often focused on the amount of space they would need to operate the roller properly.

5.2.2. The Change in Weather

This section outlines how experienced and inexperienced participants handled the sudden change in weather. Similar to the previous section the responses of the experienced participants are described first. After participants had spent four minutes in the simulation the weather changed from cloudy to rainy (see Figure 8). As the rain began to fall the participants had to decide if they would adjust the speed of their roller, and by how much. Multiple experienced participants argued that the speed of the roller (which is visible in the top right corner of the screen) was much slower than depicted. Although this suggestion will be covered later in Chapter 5.2.3. it has to be mentioned here, as it can be difficult for a participant to adjust their speed, if they are already driving the maximum speed (the software permits a speed of up to ten kilometers per hour).

Figure 8

2D Screenshot Taken during the Rain

5.2.2.1. The Approach of the Experienced Participants. Every experienced participant carefully waited at the start of the simulation, and within their minds the virtual asphalt began to 'cool down'. The experienced participants were under the impression that the virtual asphalt would behave realistically, and therefore dissipate heat at a rapid pace. It is important to note that the virtual asphalt did not actually 'cool down' within the virtual environment. The virtual asphalt did not change in temperature and participants were not aware of the temperature of the asphalt. With real asphalt roller operators can either guess the temperature by looking at the asphalt or see the temperature on a display within the roller. Even though the experienced participants could not see the 'heat' of the virtual asphalt, they still made a simple projection that the virtual asphalt would cool down, like real asphalt. Experienced participant P12 gave a clear explanation of why the temperature of the asphalt is so essential for roller operators:

> *My way of thinking is: "Every degree of temperature that is lost [within the asphalt], I'll never get back!" (…) Look, you cannot put it [the temperature] back in there, what is gone, is gone! At some point uhm.. well, you can't do anything with it [the asphalt] anymore, that's the idea. You know, you only have a limited… limited time of, of… rolling.*

During the simulation multiple experienced roller operators realized that the roller was slower than they anticipated. As a result, most of them came to the conclusion that they would never be able to compact every stretch of asphalt before it would be cold. Even though roller operators can still improve the surface texture of cold asphalt, no further compaction usually occurs when the asphalt has cooled down (Miller et al., 2011). Experienced Participant P11 explains which thoughts crossed their mind after they spent about a minute on the asphalt:

> *Well, you can see it here already, I was already getting a feeling of: "Hey, wait a minute!" To the right, the high side [of the asphalt], it will take me way too long before I get there, because I'm servicing two [paving] machines on my own.*

From this quote you can tell that experienced participant P11 was getting 'worried' about the task at hand. Note that at this point the rain had not started yet, which would eventually further exacerbate the situation. As rain of course further decreases the temperature of (un)compacted asphalt (Hashim et al., 2018). Various experienced roller operators came to the same conclusion as P11, some came to this conclusion before the rain started, others as soon as they perceived the first drops of rain. Although the timing may vary, every experienced roller operator shared the same concern. They made a negative projection of the future in which they would not able to compact the complete slab of asphalt in time. As a result, every experienced roller operator sped up their roller (if they were not already driving at the maximum speed) once the rain began. Experienced participant P18 explained why they had no other choice than to speed up their roller:

> *No, but then at least you'll have been everywhere. If… if it suddenly starts raining heavily and everything [the asphalt] is 120 degrees… and it will take you five more minutes before you get there [the right side], and it [asphalt] is already 80 degrees before you… or 70 degrees before you get there the first time. Then you're straight up too late.*

Similarly, experienced participant P19 also explained that they wanted to compact everything quickly. They also took various other elements into account (e.g. outside temperature):

> *No, of course you'll respond to that [the rain]. Well, usually you'd make sure that you'd already be closer to it [the paving machine]. Twenty-two degrees [outside temperature] is not really warm to begin with, it was windy according to the message at the start. So that's a sign for me that I had to stay closer with a top layer. So well…, if it rains, than I at least try to roll with a little more speed. To uhm… uhm… compact everything quickly! But, I couldn't…. I could not speed up.*

These examples from various experienced roller operators indicate that they consciously made the same decision. Furthermore, every experienced roller operator was able to explain their decision making and articulate the knowledge that allowed them to make these decisions. Experienced participant P11 even addressed the researcher during the simulation. They made the following remark whilst they were fully immersed in the virtual 3D environment: "*Put your drink down [joke], hop in a roller and come help me!*". This quote further illustrates that various experienced participants were consciously aware of the impact of the rain. Ultimately, only one experienced participant displayed a sign of implicit knowledge (Mancy & Reid, 2006) concerning the change in weather. Experienced participant P12 was in a peculiar position as they had not started yet when the rain began, they were still waiting in front of the asphalt. As soon as P12 perceived the rain they adjusted their sprinklers and rushed towards the asphalt to start the compaction process. During the interview experienced participant P12 found it challenging to articulate their knowledge as they could not explain very well why they suddenly rushed towards the asphalt:

> *No no… it was not… it was… it was… just like, well, now I have to, now I have to compact everything, I basically have length [to make roller passes]. I want… I don't want to say that in the rain I immediately [start] uhm… it depends on the intensity of the rain, but it definitely is a stimulus to uhm… to uhm… if it's reasonably possible to start, so to speak. But, it remains a matter of feeling.*

When the researcher asked P12 why they waited (at the start of the simulation), experienced participant P12 admitted that it came down to a 'hunch'. When the researcher asked why P12 decided to start once the rain began a similar response was provided: "*…it remains a matter of feeling.*". Even though P12 was able to articulate relevant knowledge they still referred back to the aforementioned 'subconscious feeling' that guided their hand.

It must be noted however that the rain did not affect every experienced participant equally. For experienced participant P16 the rain barely changed the simulation at all. When the researcher asked what P16 thought about the rain they used examples to explain that the effect of the rain on the asphalt in the simulation was not realistic enough:

> *Well, you literally do not know what you are doing in the simulation, because in real life you do see that. You see uhm… whether asphalt… whether it floats, or whether it uhm… moves. You can see if the asphalt cools down much faster, or not. Well, you don't see any of that here [in the simulation], the circumstances… you see some drops of rain but the asphalt is completely unaffected. (…) All you see is the droplets falling, but other than that the entire situation in the simulation does not change at all!*

It is important to note from the above explanation that experienced participant P16 was ready to use their situation awareness to perceive any changes to the asphalt within the virtual environment. They were on the lookout for blisters in the asphalt, temperature differences, floating bits of asphalt, and potentially much more. But, none of these situations came to pass and as a result P16 realized that they simply had to speed up their roller. In short, P16 did not have to change their approach drastically to counteract any serious issues caused by the rain.

5.2.2.2. The Approach of the Inexperienced Participants. Many inexperienced participants were barely affected by the rain. Inexperienced participant P02 adjusted the sprinklers of the virtual roller when the rain started but their speed did not change at all. When the researcher asked how they responded to the rain participant P02 gave the following explanation:

> *Well, maybe… a bit less speed…. [roll] a bit slower. On the one hand… well, now and then I went a little slower and sometimes a little faster. Well… actually, with rain I think it's easier to drive slower.*

Participant P02 must have been unaware of the effect that rain has on uncompacted asphalt. Slowing down will only exacerbate the situation and whilst virtual asphalt does not 'cool down', real asphalt does, especially when it rains. Various other inexperienced participants were unaffected by the rain as well, when P03 was asked whether they changed their approach the following short response followed: "*Nope, not really. I just kept driving!*". Quite similarly, P07 felt the same way: "*Nope, not really for me… for me nothing really changed.*". These statements demonstrate that many inexperienced participants perceived the rain, but they were not (yet) able to comprehend the importance of the rain. Only two inexperienced participants: P04 and P10 were affected by the rain. Participant P04 explained the thoughts that went through their head when the rain started:

> *And you try to chase the paving machines, because of uhm… all the water that falls on the asphalt. This cools the asphalt down even further. But uhm… that didn't really*

> *work because I didn't have it [asphalt] closed enough yet to get closer to the paving machines again.*

What is interesting about this explanation is that P04 also felt, like the experienced participants, that they were unable to close the gap towards the paving machines. They however, due to their limited amount of time on a roller, could not have known that the roller in the virtual environment was actually too slow. Quite similarly, inexperienced participant P10 also felt the desire to rush after the paving machines:

> *Just continue rolling as fast as possible behind the uhm… [paving] machines, to make sure everything is compacted properly. (…) Because if rain is on top [of the asphalt], that isn't too great, if you leave it around, because then it [the asphalt] will cool down very quickly.*

As a result, the conclusion can be drawn that the inexperienced participants who understood the adverse effects of the rain, subsequently adjusted the speed of their rollers.

5.2.2.3. Summary. Every experienced participant except P12 was able to articulate their approach to the change in weather. All of them were able to explain how the weather affects the asphalt and how they sought to reduce these effects during the simulation. The knowledge of most experienced operators was explicit, as they articulated detailed information about temperature windows and weather conditions. The experienced roller operators were most likely able to answer weather-related questions as all of them experienced the consequences of bad weather conditions. This is why experienced participant P16 went as far as to look around the virtual environment to see if they could perceive any asphalt related issues that would normally occur when it rains. In comparison, the inexperienced participants were mostly unaffected by the rain. All of them perceived the rain but only a few inexperienced participants comprehended its importance. As a result, most of them continued their steady space, and only two participants sped up their roller as they projected that the rain would surely affect the temperature of the asphalt.

5.2.3. Water Management & Pervious Concrete

This section covers two topics where the experienced roller operators made different decisions than their inexperienced counterparts. These additional topics did not reveal any additional implicit knowledge during the interviews. Conversely, they revealed more explicit knowledge of the experienced participants, which the inexperienced participants did not possess (yet).

5.2.3.1. Water Management. Every experienced participant checked their water before they started the compaction of the virtual asphalt. When the researcher asked various experienced participants why they adjusted their water the experienced participants produced similar explanations. Experienced participant P17 gave a great explanation:

> *At all times, whether it's raining or not. I am personally of the opinion that the rolls they have to remain wet, that's it. Because if the asphalt sticks [to the roll] you're in trouble... yes. That is the worst nightmare of every roller operator, having asphalt stick [to the roll].*

This explanation neatly illustrates the importance of water management. Various experienced operators also kept their water running during the rain. Which was often an intentional decision as experienced participant P11 explains:

> *Yes, a roller operator needs to be frugal with their water, but a good roller operator wants to know for certain that they have enough water on their rolls. If it starts to rain, and it was raining quite heavily, you shouldn't use more water than necessary. But, you have to keep in the back of your mind that the sun could come out at any moment. Maybe the rolls will become hot again, too hot and I will have forgotten to set the water back from low to mid.*

The experienced roller operators that discussed water management were all in agreement that too much water is better than too little. They could very well explain the importance of water and how they managed their water. As a result, any question from the researcher was easily answered. Most inexperienced roller operators had not used the sprinkler functionality yet, as a result most of them did not interact with this functionality within the virtual reality environment. Therefore, it is not possible to draw a comparison between the experienced and inexperienced participants as nearly every inexperienced participant did not know what to do with the sprinkler functionality.

5.2.3.2. Pervious Concrete. Most experienced participants had extensive knowledge about pervious concrete. Which the inexperienced participants were still quite unfamiliar with. Various experienced roller operators mentioned the importance of the permeability of pervious concrete (see Chapter 5.2.1.1.) and the fact that you should not vibrate the rolls as vibrations shatter the small rocks within pervious concrete (see Chapter 5.1.1.). Many inexperienced participants admitted during the interviews that they had no clue whether they should or should not vibrate with the roller. Inexperienced participant P09 was very honest about this: "*Well, I don't really know as we don't do that either here.... so I don't even know 100% for sure what it [vibrate functionality] is used for, I think I just forgot.*" As a result, no comparison can be drawn between the inexperienced and experienced participants when it comes to the type of asphalt that was used and the vibration functionality. What can be said is that the experienced participants were able to explain how the type of asphalt impacted their work and why they refrained from using vibrations.

5.2.4. Signs of Implicit Knowledge

The signs of implicit knowledge of Mancy and Reid (2006) were used to determine whether knowledge was implicit. Only three signs were encountered during the analysis of the interviews (see Table 4). The participants did not use any metaphors during the interviews which also could have been an indication of implicit knowledge (Ambrosini & Bowman, 2001).

Table 4

Signs of Implicit Knowledge that were Found

Code Name	*n*	Definition	Quotes
Signs of Implicit Knowledge			
Struggling to Articulate Knowledge	2	The participant struggles to articulate their knowledge, they may state that they find it difficult to explain themselves for example. Note: This must not be confused with a lack of knowledge.	P18: "Well, uh yes... that is difficult [to explain]. Well it is hard to express as this is something that you learn through time, because well... you can..., you cannot follow the [paving] machine right now, your roller passes will be way too short."
Reliance on Concrete Examples	1	The participant explains their knowledge through examples, they rely on practical examples to get their point across.	P12: "Well, alright, it's uhm... look if I... it depends on the weather you know, and whether it's a top layer... or whether I have to immediately be there because the layer is quite thin for example."
Surprised Understanding	2	The participant becomes aware of knowledge they possess (they may even act surprised), implicit knowledge is suddenly made explicit (to a certain degree).	P18: "Well, I never really thought about it haha."

5.2.5. Negative Feedback & Suggestions

This section is not essential for answering the research questions of this study but the substantial amount of negative feedback that the researcher received during the interviews about the simulation needs to be taken into account. The main issues revolve around the amount of asphalt that needed to be compacted and the speed of the roller. Since the paving machines did not slow down or stop, they created a large amount of uncompacted asphalt. Moreover, there were two paving machines, but there was only one roller operator. This resulted in a frustrating experience for some participants as they felt that the situation was beyond their control, a statement from experienced participant P16 describes what the simulation felt like:

> *Well, it is what I said, that the… the, the speeds, those are not in line with the real world so to speak. That uhhh…. if you want to do the entire stretch [of asphalt] and you want to drive realistically, five, six kilometers per hour. Well, I drove faster now, eight [kilometers per hour], the whole time and I didn't even have the time to do everything once in the simulation.*

Various experienced roller operators individually assessed the speed of the virtual roller and concluded that the indicated speed of 10 kilometers per hour felt more like 3 to 4 kilometers per hour. When experienced participant P18 was asked what they thought of the simulation at the start of the interview they gave the following response:

> *Well, the roller does not drive fast enough, it says that it [the roller] drives ten kilometers per hour. But I don't think it goes any faster than three kilometers per hour. It takes a really long while before you reach the [paving] machine and to go back again, before you… with two [paving] machines, you can never keep up!*

Some inexperienced participants also found the roller a little slow and the amount of asphalt overwhelming. They however did not possess enough knowledge yet to realize the severity of the situation, as (nearly) cold asphalt cannot be properly compacted anymore (Miller et al., 2011). These issues impacted the overall immersion of the experienced participants and the realism of the simulation, but on the upside many experienced participants came up with various suggestions and solutions to improve the simulation in the future. These suggestions were valuable as the experienced roller operators took their time to describe which elements were missing from the virtual 3D environment. For example, multiple experienced participants would have liked to see the temperature of the asphalt, as this is something that they would monitor if they were operating a modern roller. Experienced participant P11 for example would have liked to see the asphalt temperature:

> *Well, the [outside] temperature is 22 degrees, you later on said that uhm… that that was the outside temperature. So I thought, I will also see the asphalt temperature at some point, but t I did not see it (…). Yeah, I would have liked to see that [the asphalt temperature].*

Adding more elements to the simulation creates a richer virtual 3D environment where participants will need better situation awareness to keep track of everything. Furthermore, these suggestions will also increase the complexity of the virtual 3D environment, as more knowledge will be required to comprehend the importance of every element. For example, some participants (e.g. experienced participant P16) suggested to visually show stopping points on the virtual asphalt. Adding these visual elements means that first of all, they need to be perceived and secondly, a participant must possess the relevant knowledge to comprehend what to do with these elements. More elements also means that the situation awareness questionnaire can be improved, as more elements within the virtual 3D environment can be questioned. Coincidently, there are a few questions (see Chapter 5.1.2.) in the situation awareness questionnaire that could be replaced if there were more elements within the environment that could be questioned. As a result, these suggestions were communicated to the supervisor of the study who owns the application. These suggestions from various experienced participants are too valuable to ignore.

5.2.6. Conclusion

Previously presented evidence illustrates a stark contrast between experienced and inexperienced roller operators. In general, the experienced roller operators possessed far more explicit knowledge than their inexperienced counterparts. This is not an unexpected result as the average experienced roller operator had about twenty years of experience in the field. It was unexpected, however, that the coding process and analysis led to the conclusion that the experienced roller operators mostly relied on explicit knowledge during the simulation. The interviews revealed that some fragments of knowledge were indeed implicit, but these fragments of knowledge were not so deeply ingrained that they could not be verbalized during the interviews. The implicit knowledge that was revealed was mostly situated around the start of the simulation, as experienced participants P12 & P18 struggled to explain why they waited at the start. Whereas P18 took their time they were eventually able to explain their decision making. On the other hand, P12 gave numerous explanations but ultimately admitted that a ‘feeling’ guided their decision making. Either way, the hypothesis that experienced roller operators would struggle to explain their decision making (or verbalize their knowledge) needs to be rejected. Most experienced operators were very much able to verbalize the necessary knowledge that guided them through the virtual 3D environment. Furthermore, the hypothesis that experienced roller operators would have more situation awareness due to the implicit knowledge they possess is therefore rejected too. Almost every bit of knowledge that was communicated by the experienced roller operators was explicit in nature.

6. Discussion

6.1. Research Question

This research was conducted to assess the impact of implicit knowledge on the situation awareness of experienced and inexperienced roller operators. Whilst the overall score of the situation awareness questionnaire for the experienced operators was significantly higher, they did not score significantly higher for each individual level (e.g. projection) of the questionnaire. Furthermore, the analysis of the interviews primarily revealed explicit knowledge, which appears to be the predominant type of knowledge that roller operators utilized within the simulation. It would seem that experienced roller operators have better situation awareness, but not because they possess significantly more implicit knowledge than their inexperienced counterparts.

6.2. Interpretations

6.2.1. The Presence of Explicit Knowledge

Makarov et al. (2023) state that the quality of compacted asphalt relies heavily upon the implicit knowledge of the individual who operates the roller. Roller operators have to consider various elements (e.g. road geometry, roller type, asphalt mixture conditions) within their environment to avoid over- or under compaction at various temperatures. This is in line with the findings of Bijleveld and Dorée (2014) who confirmed during their research that the knowledge and experience of roller operators is not easy to verbalize. Based on these findings the expectations for this research were that the experienced roller operators would not always be able to explain why or how they made certain decisions within the virtual 3D environment. As implicit knowledge is inherently difficult to verbalize (Hélie & Sun, 2010; Hulstijn, 2005; Roehr-Brackin, 2022) stimuli were used during the interviews (Barton, 2015) to elicit as much implicit knowledge as possible. Surprisingly, most experienced participants were very well able to articulate why and how they made certain decisions during the interviews. Participants explained how they adjusted their work based on the asphalt mixture that was used and how the weather affected their approach for example. Very little knowledge turned out to be implicit based on the cues of Mancy and Reid (2006). An explanation for this could be that some of the knowledge Bijleveld and Dorée (2014) attempted to verbalize was deeply technical and related to specific amounts of roller passes and temperature windows for example. Most of this knowledge cannot be taught explicitly, as it is difficult to give roller operators guidelines about temperature windows, since asphalt cools down differently under varying circumstances during construction (Bijleveld, Miller, De Bondt, et al., 2015). As a result, this knowledge is often implicit, obtained through individual learning cycles that can take many years (Bijleveld, Miller, & Dorée, 2015). An alternative explanation could also be that the questions and the topics during the interviews did not require specialized implicit knowledge to answer. The virtual 3D environment did not measure exact rolling patterns or machine movements for example like the virtual reality environment of Vasenev et al. (2013). As a result, these topics could not be questioned during the interviews. Moreover, participants did not have to consider operational, logistical, and environmental factors (besides precipitation) within the simulation. As a consequence, the simulation was relatively straightforward, which potentially obviates the need for experienced participants to use specialized implicit knowledge.

6.2.2. The Ability to Perceive, Comprehend and Project

The analysis of the situation awareness questionnaire gave some unexpected results. Although the overall score of the experienced participants on the questionnaire was significantly higher, the scores for the individual levels perception and projection were not. Conversely, the score for the individual level comprehension was significantly higher for the experienced participants, as they answered every question correctly. Below the scores for each individual level are interpreted.

6.2.2.1. Differences in Perception. Perception mainly revolves around one's ability to retrieve essential information from their environment, in particular it comes down to knowing which information is important (Endsley, 2006). It was expected that the experienced roller operators would be better at perceiving important elements from their environment, due to the amount of experience they possess (Cak et al., 2020). The study of Van Benthem and Herdman (2020) for example found no relationship between experience and the situation awareness levels comprehension and projection. However, they still established that there was a significant relationship between experience and the situation awareness level perception. Interestingly, the results for the situation awareness level perception within this study deviate from the established pattern observed in various other studies (Pammer et al., 2021). To find an explanation, the answers to the questionnaire for both groups were analyzed again. Both groups answered a similar amount of questions incorrectly and for both groups the incorrect answers were evenly spread out across each question. As a result, no discernible differences could be found, and therefore it remains unclear why the scores of the experienced participants were not significantly higher, given the amount of experience they possess. A possible explanation could be that some of the questions of the SAGAT questionnaire did not tap into the detailed knowledge of the experienced participants. For example, question three ("Has the outside temperature changed?") does not require any experience with rollers to answer. As a result, it could be the case that the extensive experience of the experienced roller operators did not provide a clear advantage, as some of the questions for the level perception were quite simplistic. It is important to note that these questions were relatively simplistic because the virtual 3D environment contained fewer perceivable items compared to the real world. The virtual asphalt for example did not visually ‘cool down’ (see Chapter 5.2.2.1.) or show the stopping points that were left behind by the virtual roller (see Chapter 5.2.1.1.).

6.2.2.2. Differences in Comprehension. Comprehension revolves around one’s ability to interpret the meaning and significance of various elements that have been perceived (Endsley, 2006). The scores of the experienced participants were significantly higher than the inexperienced participants, they answered every question correctly related to the level comprehension. This score can most likely be explained by the vast amount of experience that the experienced roller operators possessed. Their experience will have allowed them to ‘pattern match’ the situation in the virtual 3D environment to similar situations that occurred in the past (Endsley 1995b). As a result, questions like “How does the weather affect your work?” or “Does the change in the outside temperature affect your work?” posed no real challenge. The experienced roller operators were able to rely on past working experiences and the knowledge they accumulated throughout the years to answer these questions. Furthermore, the scores of the experienced operators also indicate that there is room in the SAGAT questionnaire for more complicated questions that challenge their knowledge. This would probably increase the differences in scores between the experienced and inexperienced roller operators even further.

6.2.2.3. Differences in Projection. It was expected that the experienced roller operators would score significantly higher for the situation awareness level projection. Projection mainly revolves around the ability to forecast future events (Endsley, 2006) and understand how certain elements (e.g. asphalt temperature) will develop over time (Endsley, 1995b). Interestingly, the experienced participants did not score significantly higher than their inexperienced counterparts for the situation awareness level projection. This was unexpected as the experienced participants consistently explained the projections they made during the simulation in the interviews. The inexperienced roller operators on the other hand were not really concerned about the future. They did not worry about the amount of stopping points they would create by entering the asphalt too soon. Or the sheer amount of uncompacted asphalt that was still surrounding the roller near the end of the simulation. The experienced roller operators were very much concerned about the future, as they struggled to compact everything in time. If the experienced roller operators made negative projections about the future how could their situation awareness score not be significantly higher? An explanation for this could be that the situation awareness questionnaire failed to accurately assess the final level of situation awareness. An example of this could be question ten: “How long will it take until your fuel tank is empty?”. This question does assess how this element will change in the future but experienced roller operators simply do not pay attention to the fuel gauge in their roller. As they fuel the vehicle in the morning and they further do not concern themselves with this throughout the day. Some of the experienced roller operators believed this question to be a trick question as fuel is never an issue. As a result, they answered this question incorrectly, believing that the roller must be running out of fuel. Another example could be question nine: “How long will it take until your water tank is empty?” which was answered correctly by almost every participant because the question may have been too easy. This means that experienced roller operators might again not have significantly benefited from their extensive experience and knowledge. It is possible that more challenging questions would have widened the gap between the experienced and inexperienced participants.

6.3. Theoretical Implications

6.3.1. The Relationship between Experience and Situation Awareness

This study contributes to existing literature by specifically investigating the relationship between experience and situation awareness for roller operators. The results of this study indicate that there is a positive relationship between experience and situation awareness. Although numerous studies from various fields researched the relationship between experience and situation awareness (Cak et al., 2020; Carretta et al., 1996; Endsley, 2006; Hyun et al., 2006; Pammer et al., 2021) no existing study assessed this relationship for roller operators in particular. The present study analyzed the situation awareness scores of inexperienced and experienced roller operators to assess this relationship, and the results imply that there is a positive relationship. The overall situation awareness score for the experienced roller operators was significantly higher. The findings of this study build a foundation for future research as it remains unclear which individual or task related factors (Endsley, 1995b) contribute to this difference. As previous research accentuates the importance of implicit knowledge (Bijleveld & Dorée, 2014) it was assumed that higher scores within the experienced group could be explained by the presence of implicit knowledge. Conversely, only minimal amounts of implicit knowledge were found during the stimulated recall interviews, which implies that implicit knowledge may not be as impactful as previously anticipated. Be that as it may, the significant difference in situation awareness scores for the level comprehension could imply that another individual factor from Endsley’s model (1995b) may be impacting this relationship. Every experienced participant answered each situation awareness question for the level comprehension correctly. According to Endsley (2006) it is very difficult to understand the importance of elements within an environment without existing mental models. Which would imply that these impressive results were potentially achieved by the presence of detailed mental models.

Individuals with well-developed mental models can more easily identify which elements are important and quickly understand how these elements interact with one another. This could explain why the experienced participants were able to answer every question correctly. In summary, the results of this study imply that there is a positive relationship between experience and situation awareness for roller operators. This distinction could not be explained by the presence or absence of implicit knowledge, but there is an indication that this difference could be explained by other individual factors like mental models (Endsley, 2006).

6.3.2. Explicating Knowledge through Virtual Reality

This study contributes to existing literature by providing a new perspective on the overall knowledge of roller operators. Existing literature suggests that conventional compaction depends on the implicit knowledge of the roller operator (Makarov et al., 2023) and that said roller operator will struggle to verbalize the implicit knowledge that they need for conventional compaction (Bijleveld & Dorée, 2014). The results of this study however paint a different picture as the experienced participants were able to verbalize most, if not all of the knowledge they used during the simulation. It must be noted that the results of this study do not deny the existence of deeper rooted implicit knowledge, but rather this research shows that experienced roller operators possess a substantial amount of explicit knowledge that could be articulated. First and foremost, these findings could imply that the elicitation technique that was used during the research worked (Barton, 2015) and that recordings of the participants were a good stimulant for explicating implicit and explicit knowledge. Secondly, these results also imply that future research could employ virtual reality to explicate specific knowledge from roller operators. As previous research mainly observes on-site construction processes to explicate the knowledge of roller operators (Bijleveld, Miller, & Dorée, 2015). Of course, virtual environments are not capable of fully replicating real work environments with all their intricacies yet. However, most participants thought deeply about the choices they made and why they made them when they watched the recordings of their performance within the virtual 3D environment. In summary, the results of this study imply that experienced roller operators possess a wealth of explicit knowledge, additionally, the results also demonstrate that virtual reality could serve as a unique approach for explicating (implicit) knowledge.

6.4. Practical Implications

6.4.1. The Educational Value of Virtual Reality

On a practical level, the study highlights the educational properties of virtual reality. It is not without reason that the use of virtual reality technology in education has become more widespread throughout recent years, especially since the COVID-19 pandemic (Rojas-Sánchez et al., 2023). The inexperienced participants of the study were road construction students in their vocational education. Occasionally these students would evaluate their performance during the interviews by studying their screen recording and commenting on the actions they took. For example, inexperienced participant P05 started in the middle of the road during the simulation, but as soon as they had to explain why they started in the middle the following happened: "*It maybe would have been better if I well… started on the left side [of the road] and then worked my way towards the middle.*" Various other inexperienced participants regularly commented on the mistakes they made and the thoughts associated with them. Which is an indication that these students learned something by watching the recording of their own performance. This was an unintentional side effect of the study, but it does illustrate that a roller simulator could fulfill multiple purposes for students of road construction as they learn the tools of the trade. One of the inexperienced participants explained after the interview that they worked with various simulators during their education but never a simulator where a virtual roller could be controlled. They were of the opinion that a finalized prototype of this simulator could definitely be introduced at some point to introduce students to unique scenarios that cannot be practiced in the real world yet. In summary, the research highlighted the educational value of virtual reality as various students evaluated their actions and learned from their mistakes during the interviews.

6.4.2. The Complexity of Virtual Reality Environments

The amount of feedback and suggestions the researcher received during the interviews illustrates that the virtual 3D environment had some issues. The experienced participants were honest about their experience as they came up with numerous creative ideas to improve the virtual 3D environment. As a result, the researcher realized that an experienced practitioner should have been consulted before the virtual environment was used for research. Of course, experts were consulted when the application was developed, years before this research. However, the results of this study do indicate that it is a good idea to keep an experienced practitioner in the loop, to ensure that the virtual environment remains free of glaring issues. This practical suggestion is quite broad, but nonetheless, it remains a valuable insight from this research. A few experienced roller operators even volunteered to come to the University of Twente in the (near) future to support further development of this virtual 3D environment by giving feedback.

6.4.3. The Knowledge Gap Between Participants

As the inexperienced participants were at the end of the second year of their vocational education a knowledge gap was to be expected. It is difficult to assess how large this knowledge gap truly is as these students still have a third year ahead of them, and some of the missing knowledge may be taught in their final year. Therefore, the following statements need to be interpreted with caution, as it might well be the case that the identified gap is no longer present as soon as these students obtain their degrees. First and foremost, the inexperienced roller operators were not worried about the temperature of the asphalt at all. This is an indication that they were most likely not aware that cold asphalt cannot be compacted anymore (Miller et al., 2011). This is a basic characteristic of asphalt that is essential to keep in mind, which is why the experienced roller operators were so worried about the temperature of the asphalt. Secondly, most of the inexperienced participants did not know what to do with the sprinklers or the vibration functionality. Every experienced participant turned their sprinklers on, whereas most inexperienced participants left the sprinkler functionality untouched. The experienced roller operators explained that compacting asphalt without water can result in various issues, like asphalt sticking to the rolls. Finally, the inexperienced participants did not alter their behavior based on the type of asphalt. The experienced operators took the properties of pervious concrete into account before approaching the asphalt. Based on the identified knowledge gaps the following practical suggestion was formulated. If the aforementioned knowledge gaps are not covered in the third year (or if they have already been addressed) then it may be appropriate to discuss the topics of asphalt temperature, water management, and asphalt types in greater detail. These students will most definitely need this knowledge when they start working in the asphalt construction industry.

6.5. Limitations

6.5.1. The Questions of the Situation Awareness Questionnaire

The quantitative results of this study confirm a positive relationship between experience and situation awareness for roller operators. These results, however, should be considered with the following limitations in mind. Firstly, only ten of the original twelve questions were used to determine the situation awareness scores of every participant. Two questions were left out as these questions could only be answered with information from the ‘virtual meeting page’ (see Chapter 5.1.1.). As a result, less data was used to calculate the scores of the situation awareness levels perception and projection. As there were fewer questions for these levels there was also less room for participants to demonstrate their ability to perceive elements from the environment and project their status in the (near) future. From a positive perspective, the results of the situation awareness questionnaire remain valid as the researcher removed the questions that did not asses situation awareness. However, the results are based on less data than originally planned. Secondly, question ten

(“How long will it take until your fuel tank is empty?”) was occasionally interpreted as a trick question by the experienced participants and as a result, some experienced participants answered this question incorrectly. Question ten was not removed from the data analysis as the answer was visible within the virtual 3D environment. As a result, question ten impacts the scores of the level projection for some experienced participants and this may explain why they did not score significantly higher than their inexperienced counterparts. Since the sample is already relatively small these minor mistakes can impact the analysis of the data. Finally, for the level projection, the experienced operators did not score significantly higher than the inexperienced operators. Whether this was caused by the removal of question eight, or the wrongful interpretation of question ten remains uncertain. However, it must be noted that the experienced participants were significantly more worried about the future than their inexperienced counterparts (see Chapter 6.2.2.), which indicates that the findings of the qualitative analysis do not fully align with the scores of the questionnaire. In other words, based on the qualitative analysis one would assume that the situation awareness scores for both groups for the level projection would be significantly different. The remaining questions may have been too easy, as they did not cover some of the complex topics that the experienced operators made projections about during the interviews. In summary, the results of the situation awareness questionnaire provide a good indication of the difference in situation awareness between experienced and inexperienced roller operators. That being said, the scores need to be interpreted carefully as there was less data than originally intended, question ten was wrongfully interpreted as a trick question by some experienced participants and some findings of the qualitative analysis do not align with the quantitative analysis.

6.6. Recommendations

6.6.1. Visualize Stopping Points in the Virtual 3D Environment

Future studies could further examine the fine line between implicit and explicit knowledge by improving various aspects of the virtual 3D environment. One such aspect is the visibility of ‘stopping points’ for example. If those are visible, the amount of stopping points, their placement, and whether they have been addressed throughout the simulation or not, could be analyzed. This may reveal valuable implicit knowledge of how experienced roller operators structure and address the stopping points they leave behind. It is essential that roller operators stop their roller on an angle at the end of every pass, and that they roll through previous stop points in the next pass (Hand et al., 2021). Doing so prevents the formation of bumps and dips on the asphalt (Volvo CE, 2022). A similar approach to the design of this study could be employed where participants see a recording of the session and a map of all the stopping points they left behind. Additionally, the current situation awareness questionnaire could be updated with new questions as well. These questions could assess the situation awareness of roller operators on the stopping points they addressed and the ones that were neglected. Interesting questions could be implemented like: “Where did you leave your last stopping point, and has this stopping point been addressed yet?”. These questions will directly assess the situation awareness that experienced roller operators need on a daily basis, as roads are ideally constructed without bumps and dips. In summary, by improving this aspect of the virtual 3D environment future research could uncover essential implicit or explicit knowledge related to stopping points. This adjustment to the virtual 3D environment would also make the simulation more realistic as the virtual asphalt reacts to the placement of the roller. As a result, participants will need to pay closer attention to the virtual asphalt, which challenges their situation awareness. On a final note, the researcher would also recommend to make various adjustments to the virtual 3D environment based on the feedback and suggestions that were gathered during this study.

6.6.2. The Presence of Detailed Mental Models

The goal of this study was to analyze implicit knowledge to see if this individual factor could be responsible for the difference in situation awareness between experienced and inexperienced participants. Contrary to expectations, implicit knowledge did not turn out to be as influential as anticipated. Therefore, the question remains which individual factors from Endsley’s (1995b) model (see Figure 1) heavily influence the situation awareness of roller operators? The study believes that future research could investigate the mental models of various experienced roller operators as mental models are an important individual factor that influences situation awareness (Endsley, 1995b). Bijleveld and Dorée (2014) made a similar suggestion for future research as the mental models of roller operators have not been investigated yet. In this research the experienced participants answered every situation awareness question related to the level comprehension correctly, which is only possible with the presence of good mental models according to Endsley (2006). Additionally, good mental models also allow individuals to make better predictions and project possible futures (Endsley, 1995b). Which may explain why the experienced operators were so concerned about the future. The results of this study therefore indicate that mental models could be an influential individual factor that may explain the difference in situation awareness between experienced and inexperienced roller operators. As a result, future research could explicate the mental models of inexperienced and experienced roller operators whilst also using the virtual 3D environment to gather situation awareness scores. It is important to note that the aforementioned improvements to the virtual 3D environment are also relevant for this research direction. In summary, future research could investigate the remaining individual factors to assess their influence on the situation awareness of roller operators. To that end, the mental models of both experienced and inexperienced roller operators could be a promising avenue for future research.

7. Conclusion

At the start of this study implicit knowledge was identified as an essential individual factor (Bijleveld, Miller, & Dorée, 2015) that could explain the difference in situation awareness between experienced and inexperienced roller operators. As a result, this study set out to assess the situation awareness of both experienced and inexperienced roller operators. To determine if the situation awareness of the experienced participants would indeed be higher, which is often the case in other fields (Endsley, 2016). Subsequently, the knowledge of all the operators was assessed. By using the recordings of the performances of the participants as stimuli (Barton, 2015), potential implicit knowledge was to be uncovered. Any valuable implicit knowledge that was found could then be shared with less experienced roller operators to improve their situation awareness as well.

As expected, the overall situation awareness scores of the experienced participants were significantly higher. They may not have been significantly higher for each level of situation awareness but the data does illustrate that experienced participants have the upper hand when it comes to situation awareness. Now, the question remained whether this difference was caused by the presence or absence of implicit knowledge. Unexpectedly, almost every experienced participant was able to explain the decisions they made by verbalizing the necessary knowledge. This would imply that the situation awareness of the experienced participants was not better due to the presence of implicit knowledge. As most experienced operators were able to answer challenging questions from the researcher without showing any signs of implicit knowledge (Mancy & Reid, 2006). Therefore, this study can only conclude that implicit knowledge does not influence the situation awareness of experienced roller operators as much as anticipated. Other individual factors from Endsley's Model (1995b) may be responsible for this difference, which can only be determined through further research.

Finally, unlike at the start of this research, a new foundation has been established by comparing the situation awareness scores of experienced and inexperienced roller operators. Initially, there were no indications of which individual factors from Endsley's Model (1995b) would be influential. However, now there are various suggestions for new research, and the importance of implicit knowledge in this context has been thoroughly assessed.

8. References

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9. Appendix

Appendix A: Situation Awareness Questionnaire

The table below provides an overview of the questions that were part of the SAGAT questionnaire. The table indicates the level of situation awareness each question intended to evaluate, and whether or not the answer to that question was automatically evaluated.

Table 5

SAGAT Questionnaire

Nr.	Question (Dutch)	Question (English)	Level	Evaluation
1.	Hoe vaak heb je het aangegeven gebied al gewalst?	How many times have you compacted the indicated area?	Perception	Manual
2.	Welke kant van het asfalt is de lage kant? Kies een blauw vlak.	Which side of the asphalt is the low side, choose a blue area.	Perception	Automatic
3.	Is de buiten temperatuur veranderd?	Has the outside temperature changed?	Perception	Automatic
4.	Wat is de huidige weerssituatie?	What is the current weather situation?	Perception	Automatic
5.	Met welke walsfase ben je nu bezig?	Which rolling phase are you working on now?	Comprehension	Automatic
6.	Welke invloed heeft het weer op jouw werk?	How does the weather affect your work?	Comprehension	Automatic
7.	Heeft de verandering in de buiten temperatuur invloed op jouw werk?	Does the change in the outside temperature affect your work?	Comprehension	Automatic
8.	Mag je de trilfunctie nu aanzetten?	Can you turn on the vibration function now?	Comprehension	Automatic
9.	Hoe lang duurt het nog tot je watertank leeg is?	How long will it take until your water tank is empty?	Projection	Automatic
10.	Hoe lang duurt het nog tot je brandstoftank leeg is?	How long will it take until your fuel tank is empty?	Projection	Automatic
11.	Hoe vaak moet je het aangegeven gebied nog walsen, denk je, om de juiste verdichting te bereiken?	How many times do you think you need to roll the indicated area to achieve the correct compaction?	Projection	Manual
12.	Zorgen de huidige weersomstandigheden voor een verandering in de manier waarop jij de taak moet afronden?	Are the current weather conditions changing the way you have to complete the task?	Projection	Automatic

Appendix B: Interview Question Types

Four types of questions were used during the interviews to expose the implicit knowledge of each participant. These types of questions are based on the recommendations of Van Braak et al. (2018):

1. Questions that are neutral and open ended (e.g. “What is happening here?”).
2. Questions that describe an observation (e.g. “You increased your speed at this point?”).
3. Questions that ask for intentions/aims (e.g. “What did you hope to achieve with compacting this stretch of asphalt first?”).
4. Questions that are evaluative of nature (e.g. “What did you think of your approach?”).

Appendix C: Informed Consent

Informatieblad voor onderzoek 'Omgeving Bewustzijn Tijdens het Walsen'

Doel van het onderzoek
Dit onderzoek wordt geleid door M. Pluijmaekers.
Het doel van dit onderzoek is om te analyseren hoe bewust wals operatoren zich zijn van hun directe omgeving gedurende het werk. Het onderzoek wil vast stellen of bepaalde kennis van sommige participanten het bewustzijn van de directe omgeving kan vergroten.

Hoe gaan we te werk?
U neemt deel aan een onderzoek waarbij we informatie zullen vergaren door:

- U een wals te laten besturen in een virtuele 3D omgeving (VR). Na het voltooien van de opdracht krijgt u een korte digitale vragenlijst over uw ervaring. Uw prestaties in de virtuele 3D omgeving worden tevens opgenomen.
- Sommigen van u te interviewen. Gedurende dit interview worden opnames van de virtuele 3D omgeving bekeken. Uw antwoorden worden middels een audio-opname vast gelegd en op een later tijdstip wordt er een transcript uitgewerkt.

Potentiële risico's en ongemakken

- Er zijn geen fysieke, juridische of economische risico's verbonden aan uw deelname aan deze studie. U hoeft geen vragen te beantwoorden die u niet wilt beantwoorden. Uw deelname is vrijwillig en u kunt uw deelname op elk gewenst moment stoppen.
- Er bestaat een zeer kleine kans dat u als deelnemer licht wagenziek raakt van de virtuele 3D omgeving. Dit kan zich uiten als lichte misselijkheid of duizeligheid. Indien dit het geval is dient u dit direct aan te geven aan de onderzoeker en de VR headset van uw hoofd te verwijderen. Deze klachten trekken na het verwijderen van de headset binnen een aantal minuten weg.

Vergoeding
U ontvangt voor deelname aan dit onderzoek geen vergoeding .

Vertrouwelijkheid van gegevens
Wij doen er alles aan uw privacy zo goed mogelijk te beschermen. Er wordt op geen enkele wijze vertrouwelijke informatie of persoonsgegevens van of over u naar buiten gebracht, waardoor iemand u zal kunnen herkennen.
Voordat onze onderzoeksgegevens naar buiten gebracht worden, worden uw gegevens zoveel mogelijk geanonimiseerd, tenzij u in ons toestemmingsformulier expliciet toestemming heeft gegeven voor het vermelden van uw naam, bijvoorbeeld bij een quote.

In een publicatie zullen anonieme gegevens of pseudoniemen worden gebruikt. De audio-opnamen, formulieren en andere documenten die in het kader van deze studie worden gemaakt of verzameld, worden opgeslagen op een beveiligde locatie bij de Universiteit Twente en op de beveiligde (versleutelde) gegevensdragers van de onderzoekers.
De onderzoeksgegevens worden bewaard voor een periode van 10 jaar. Uiterlijk na het verstrijken van deze termijn zullen de gegevens worden verwijderd of worden geanonimiseerd zodat ze niet meer te herleiden zijn tot een persoon.
De onderzoeksgegevens worden indien nodig (bijvoorbeeld voor een controle op wetenschappelijke integriteit) en alleen in anonieme vorm ter beschikking gesteld aan personen buiten de onderzoeksgroep.

Tot slot is dit onderzoek beoordeeld en goedgekeurd door de ethische commissie van de faculteit BMS (domain Humanities & Social Sciences).

Vrijwilligheid
Deelname aan dit onderzoek is geheel vrijwillig. U kunt als deelnemer uw medewerking aan het onderzoek te allen tijde stoppen, of weigeren dat uw gegevens voor het onderzoek mogen worden gebruikt, zonder opgaaf van redenen. Het stopzetten van deelname heeft geen nadelige gevolgen voor u of de eventueel reeds ontvangen vergoeding.
Als u tijdens het onderzoek besluit om uw medewerking te staken, zullen de gegevens die u reeds hebt verstrekt tot het moment van intrekking van de toestemming in het onderzoek gebruikt worden.

Wilt u stoppen met het onderzoek, of heeft u vragen en/of klachten? Neem dan contact op met de onderzoeksleider.

Naam: M. Pluijmaekers
Mail: m.n.e.j.pluijmaekers@student.utwente.nl

Voor bezwaren met betrekking tot de opzet en of uitvoering van het onderzoek kunt u zich ook wenden tot de Secretaris van de Ethische Commissie / domein Humanities & Social Sciences van de faculteit Behavioural, Management and Social Sciences op de Universiteit Twente via ethicscommittee-hss@utwente.nl. Dit onderzoek wordt uitgevoerd vanuit de Universiteit Twente, faculteit Behavioural, Management and Social Sciences. Indien u specifieke vragen hebt over de omgang met persoonsgegevens kun u deze ook richten aan de Functionaris Gegevensbescherming van de UT door een mail te sturen naar dpo@utwente.nl.

Tot slot heeft u het recht een verzoek tot inzage, wijziging, verwijdering of aanpassing van uw gegevens te doen bij de Onderzoeksleider.

Door dit toestemmingsformulier te ondertekenen erken ik het volgende:

1. Ik ben voldoende geïnformeerd over het onderzoek door middel van een separaat informatieblad. Ik heb het informatieblad gelezen en heb daarna de mogelijkheid gehad vragen te kunnen stellen. Deze vragen zijn voldoende beantwoord.
2. Ik neem vrijwillig deel aan dit onderzoek. Er is geen expliciete of impliciete dwang voor mij om aan dit onderzoek deel te nemen. Het is mij duidelijk dat ik deelname aan het onder- zoek op elk moment, zonder opgaaf van reden, kan beëindigen. Ik hoef een vraag niet te beantwoorden als ik dat niet wil.

Naast het bovenstaande is het hieronder mogelijk voor verschillende onderdelen van het onderzoek specifiek toestemming te geven. U kunt er per onderdeel voor kiezen wel of geen toestemming te geven. Indien u voor alles toestemming wil geven, is dat mogelijk via de aanvinkbox onderaan de stellingen.

	JA	NEE
3. Ik geef toestemming om de gegevens die gedurende het onderzoek bij mij worden verzameld te verwerken zoals is opgenomen in het bijgevoegde informatieblad. Deze toestemming ziet dus ook op het verwerken van gegevens betreffende mijn leeftijd, gender en jaren ervaring die ik heb als wals operator.	☐	☐
4. Ik geef toestemming om tijdens het interview opnames (geluid & beeld) te maken en mijn antwoorden uit te werken in een transcript.	☐	☐
5. Ik geef toestemming om mijn antwoorden te gebruiken voor quotes in de onderzoekspublicaties.	☐	☐
6. Ik geef toestemming om de bij mij verzamelde onderzoeksdata te bewaren en te gebruiken voor toekomstig onderzoek en voor onderwijsdoeleinden.	☐	☐
7. Ik geef toestemming voor alles dat hierboven beschreven staat.	☐	

Naam Deelnemer:

Handtekening:

Datum:

Naam Onderzoeker: M. Pluijmaekers

Handtekening:

Datum: xx-xx-xxxx

Appendix D: General Information Questionnaire

Below you will find an overview of the questions that are in the questionnaire on Microsoft Forms. Please note that every question is mandatory and that the online questionnaire is dynamic, the answers of the participants affect the questionnaire. The Form in Microsoft Forms can be accessed with the following link: https://forms.office.com/e/Up0TrHddGi.

Table 6

General Information Questionnaire

Number	Question (Dutch)	Question (English)	Visibility
1.	Wat is uw voor- en achternaam?	What is your first and last name?	Always
2.	Wat is uw leeftijd?	What is your age?	Always
3.	Wat is uw gender?	What is your gender?	Always
4.	Bent u op dit moment nog bezig met een opleiding?	Are you currently studying for a degree?	Always
5.	Welke opleiding bent u mee bezig?	Which degree are you studying for?	Dynamic
6.	Wat is uw huidige opleidingsniveau?	What is your current level of education?	Dynamic
7.	Heeft u al ervaring met walsen in een virtuele omgeving?	Do you have experience with asphalt compaction in a virtual environment?	Always
8.	Zou u deze ervaring als positief omschrijven?	Would you describe this experience as positive?	Dynamic
9.	Speelt u wel eens een game op een console, telefoon of computer?	Do you ever play a game on a console, phone or computer?	Always
10.	Wilt u een samenvatting van de resultaten van deze studie ontvangen via de mail?	Would you like to receive a summary of the results of this study via mail?	Always
11.	U kunt hier uw mail adres invullen.	You can enter your mail address here.	Dynamic

Appendix E: Instructions for the Virtual 3D Environment

Participants needed to go through multiple steps before they could actually wear the virtual reality headset and operate the roller. The text below outlines the information and instructions that were provided to every participant. Even though the outline below is in English the information was communicated to the participants in Dutch.

1. **Start of the Session:** Participants were welcomed and they were presented with a general outline of the steps that needed to be taken before the session on the virtual roller could begin. This outline was communicated verbally. The order and importance of the following steps were explained:
    a. **Informed Consent:** Participants needed to sign a physical informed consent, which was essential as the research could otherwise not proceed.
    b. **Microsoft Forms:** Then, participants needed to go through an online questionnaire to capture their demographics.
    c. **Working Experience:** Lastly, participants were questioned on their working experience, the number of hours per week, and the years that they had spent on a roller.
2. **Working in the Virtual Environment:** Now the time came for participants to take a seat behind the steering wheel and the virtual roller. Again, a verbal outline was provided of the various steps that the participant would encounter.
    a. **General Outline:** Participants were told that they would first see a Welcome screen where they should enter their Participant Number (e.g. ‘P14’, in other words, ‘Participant 14’). Subsequently, they would find themselves on a Work Meeting page where information is provided about the task at hand (e.g. “What type of asphalt are we using today?”). Participants were also informed that they would see a short tutorial about the steering wheel and the joystick. Finally, every participant was also told, in advance, that there would be a questionnaire at the end.
    b. **Virtual Reality Simulation:** As soon as the paving machines appeared on the screen the researcher helped the participant with putting on the Oculus Rift S headset. From that point onwards each participant went to work in the virtual environment.
    c. **SAGAT Questionnaire:** After the simulation concluded the questionnaire appeared and each participant was able to answer the various questions.
3. **End of the Session:** Each participant was thanked for their efforts and prepared for the upcoming interview.

Appendix F: Frequently Asked Questions (FAQ)

The following list was created before the research was conducted and updated during the research so that every participant received the same response to their questions.

Table 7

Frequently Asked Questions (FAQ)

Number	Question (English)	Answer (English)
1.	How long does the actual simulation last?	The simulation lasts eight minutes.
2.	Do the buttons on the joystick do anything?	The buttons on the joystick have no purpose, aside from the button on the top that starts the engine.
3.	Do the buttons on the wheel do anything?	Aside from the paddle shifters, all other buttons on the wheel serve no purpose.
4.	Do I need to adjust the vibration or sprinklers?	That is completely up to you, use them as you see fit during the simulation.
5.	Will I have enough time to compact everything?	You do not have enough time to properly compact the entire motorway, but that is fine.
6.	I have done '…' what should I do next?	Good question, unfortunately, I cannot tell you what you should do next, that is up to you.
7.	How do I start the engine of the roller?	Press the button on the top of the joystick to start the engine and the simulation.
8.	Can I wear my glasses during the simulation?	Yes, you can! The Oculus Rift S is big enough to accommodate regular glasses.

Appendix G: Contact Information vCard QR Code

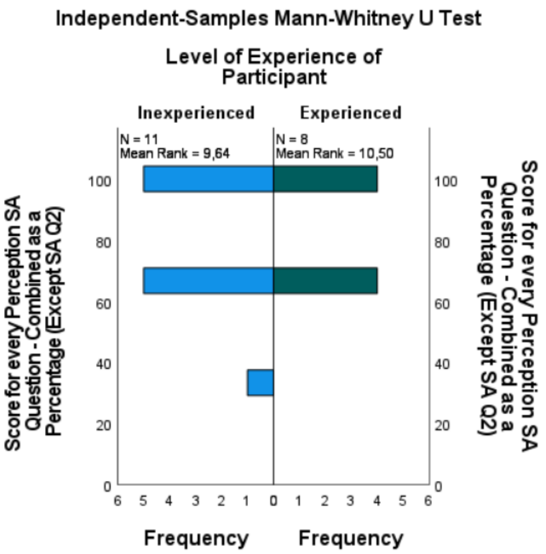
To allow participants to ask follow-up questions (at a later stage) the researcher provided his contact information via a vCard QR code during the debriefing of each participant.

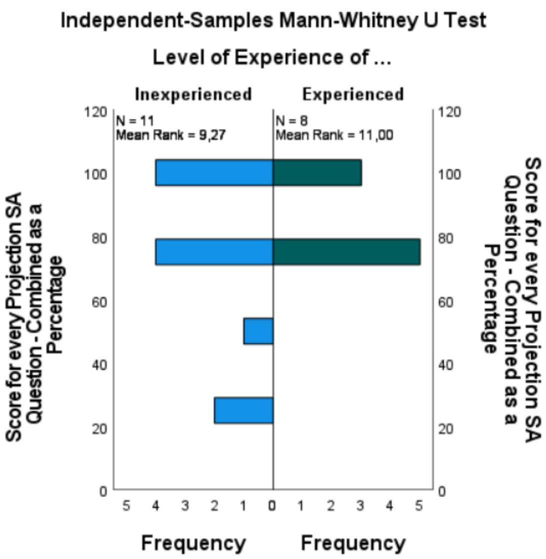
When participants scanned the QR code on the left the following information was added to their contacts application:

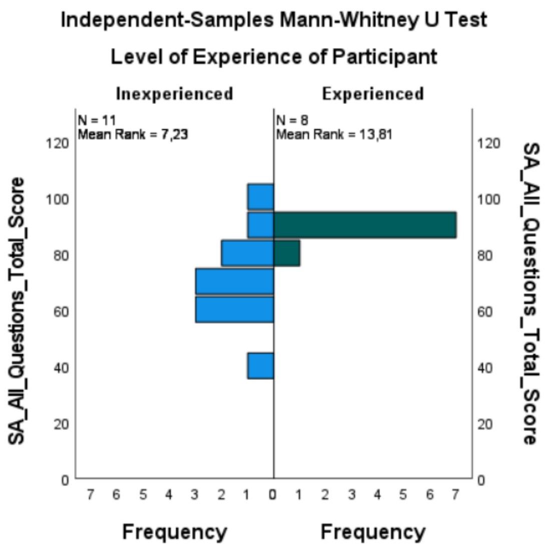
- First and last name of the researcher.
- Mail address of the researcher.
- Website of the University of Twente.

Appendix H: Visualization of the Questionnaire Data

The below histograms were created with SPSS to assess the distribution of the data from the situation awareness questionnaire. The histograms for the levels perception and projection are somewhat bimodal. The comprehension histogram has a bell shape for the inexperienced participants and a single peak for the experienced participants, as every participant achieved the maximum score for this level. The histogram for the overall scores is slightly skewed for the inexperienced participants, whereas the histogram for the experienced participants displays another peak.







Appendix I: Codebook for the Interviews

The table below contains the final codebook which includes examples to illustrate each code. Not every code was important for the research question of this particular study, but the researcher felt inclined to code all the feedback that was provided as well. This feedback can be used to further improve the roller simulation application for future research. Every real example is from the actual interviews and has been translated from Dutch to English by hand, to ensure every statement is still accurate.

Table 8

Final Codebook for the Stimulated Recall Interviews

Code Name	Definition	Real Example
Feedback: Negative		
Asphalt between machines	Participant indicates that there is room between the paving machines but this is not reflected in the stretch of asphalt that is visible.	P08: “I found it strange that this area has been filled with asphalt as the machines have not been there?”
Asphalt is unaffected by rain	Participant mentions that the asphalt does not respond to the rain as asphalt is normally affected by rain.	P16: “In real life you see… uhhh, that asphalt…, that it floats or slides around due to the rain.”
Controls are not realistic	Participant indicates that the controls (steering wheel & joystick) are not realistic.	P15: “You don’t have all of this and the buttons are totally different!”
Difficult to assess where you have been	Participant is unable to assess what parts of the asphalt they have compacted thus far and which parts have not been compacted yet.	P05: “I found it a little unclear what I had compacted and what I had not compacted yet.”
Generally negative feedback	Participant makes a negative remark that is not specifically related to anything (e.g. it was not fun).	P15: “I did not like it!”
No overview from the roller	Participant states that they struggle to 'see' from the cabin of the roller. They may feel like they are further away from something than in reality or vice versa.	P13: “No, the feeling is gone, and you don’t see any depth.”
Physical joystick moves around	Participant states that the joystick moved on the table when they attempted to operate the joystick.	P05: “I found that, yes… you felt it, if you moved it all the way to the front, yes… you felt it at the back, it came up!”
Roller has no ‘crab steering’	Participant states that the roller does not come equipped with a 'crab steering' functionality (Dutch: ‘hondengang’).	P12: “I usually create these patterns by crab steering the roller, but I cannot do that here.”
Roller speed too low	Participant states that the roller moves too slow compared to the real world. In	P18: “Well, the roller doesn’t drive fast enough, it says that it drives ten kilometres per hour.

Code Name	Definition	Real Example
	other words, the speed that is shown on the screen during the session is incorrect.	But I don't think it goes any faster than three kilometres per hour."
Roller starts too close to the asphalt	Participant states that the roller starts too close to the asphalt, this makes it harder to steer the roller in the beginning.	P11: "Yes, but the roller was too close to the seam to start at the bottom."
Simulation is graphically not impressive	Participant indicates that the virtual environment is graphically not impressive.	P03: "Well, it was of course uhh… quite basic, the 'pixels' and such.
Simulation is not realistic	Participant states the simulation is not realistic.	P20: "It's not very realistic yet, but maybe it will in the future, those things change."
Stopping points are not visible	Participant states that the stopping points they create with the roller are not visible. This is usually something roller operators keep track of.	P19: "A stopping point where I stopped, that you can see those clearly. I did not see them."
Too much asphalt for one roller operator	Participant exclaims that there is simply too much asphalt to cover for one roller operator.	P20: "To be honest you're missing another roller. Normally if there are two paving machines then there are two rollers, at least."
Unable to see the rolls	Participant states that they are unable to see the rolls of their roller, either via one of the mirrors or with their own eyes.	P19: "I can see the side of the roller but I don't see the rolls of the roller."
Unable to see what high and low is	Participant cannot tell based on the simulation where the "high" or the "low" side of the asphalt is.	P11: "I slowly worked my way up, I did not see a camber in the road".
Feedback: Positive		
360 degrees is good	Participant makes a positive remark about the 360 degrees view angle within the simulation.	P07: "I haven't done this quite a lot [virtual reality], but it was quite nice that you can look around 360 degrees."
Generally positive feedback	Participant makes a positive remark that is not specifically related to anything (e.g. it was fun, the simulation was interesting, it was great to try).	P04: "It was quite cool to do!"
Good overview from roller	Participant states they have a good overview from the roller, they are able to see the things they need to see.	P17: "You can nicely see what you… what you do [in the simulation]."
Mirrors are great	Participant expresses that they either found the mirrors useful, and easy to use or they found them a good addition to the virtual environment.	P07: "Yes, nice functionality that the mirrors work actually".
Rain looks good	Participant states the rain looks good.	P01: "I liked it [the rain], nicely made."

Code Name	Definition	Real Example
Simulation looks “realistic”	Participant states that the simulation resembles the real world (to a certain degree), in other words: "the simulation looks realistic".	P14: “It’s realistic, uhm, for this method of paving asphalt, it is realistic enough.”
Simulation looks “pretty”	Participant states that the simulation (or a part of the simulation, e.g. the roller) looks pretty, in this case they are not referring to 'realism' but to the graphical quality of the product.	P07: “I found it… I was surprised. I thought it would look a little less pretty. Still looked quite nice.”
Virtual Joystick Moves	Participant makes a positive remark about the virtual joystick.	P10: “Yes, because the joystick moved forward [in the simulation], I found that interesting.”
Feedback: Suggestions		
Add ‘crab steering’	Participant suggests that 'crab steering' (Dutch: ‘hongengang’) should be added to the simulation as this is an essential part of the type of roller that was used for the simulation.	P17: “Yes… yes, indeed. With my own machine of course I’m used to working with ‘crab steering’.”
Add ‘cruise control’	Participant suggests to add cruise control as with a real roller they set a certain speed, they do not have to keep their hand on the joystick (technically).	P12: “I can’t the whole time with the… with the driving lever can’t be looking all the time how fast I’m going. With the roller you have to be able to adjust that. Like a ‘cruise control’ so to speak.”
Add ‘NPCs’	Participant states they would like to have seen construction workers in-and-around the paving machines (NPCs are non-playable-characters, which is a common term in gaming).	P19: “That’s something I missed. As a roller operator you have to wait sometimes, because a construction worker has to add a little [asphalt] with their rake or shovel.”
Add ‘stopping points’	Participant indicates that they would like to see "stopping points" in the simulation as they usually pay attention to them when they are operating a roller in real life.	P19: “A stopping point where I stopped, that you can see those clearly. I did not see them.”
Add ‘visible heat’ to asphalt[2]	Participant suggests that the heat of the asphalt should be visible within the virtual 3D environment. In other words, you can visibly tell from the	P13: “Yes, the movement of the asphalt and everything, you can see the warmth!”.

[2] This particular code was added to the codebook based on a suggestion of the other EST student. She came to the conclusion that this code was missing during the ICR assessment.

Code Name	Definition	Real Example
	virtual asphalt that it’s hot, not from a temperature gauge.	
Add a ‘storm drain’	Participant suggests including a "storm drain" or "curb inlet" which indicates to what side the water needs to flow.	P19: “You could maybe for the imagery add a storm drain over here, next time…”
Add a ‘top view’ camera angle	Participant suggest to add a new camera angle where you can see the roller from the top.	P14: “Look, with this of course you learn about stopping points and such, but actually you should look at all of this from the top.”
Add a ‘spreader’	Participant suggests to add a "spreader" ('strooier') which spreads a tiny layer of stones/asphalt on the road before compaction.	P19: “And, I am missing a spreader [in the simulation]!”
Add a second roller	Participant suggests to add another roller to the simulation, as there is too much asphalt for one operator.	P06: “Then uhm… then uhm… two rollers might be better for this job.”
Add additional mirrors	Participant suggests that more mirrors are necessary to see the rolls of the roller for example.	P12: “The rolls cannot be seen, and that is exactly what this is about for me within the simulation... front and rear rolls must have front mirrors and rear mirrors.”
Adjust speed of the roller	Participants suggests how fast the roller should be, the participant makes a recommendation for how the speed of the roller should be altered or the participant indicates how fast they believed the roller to be.	P16: “Yes, well, I think regarding the simulation, it can… it can certainly go twice as fast compared to now.”
Display asphalt temperature	Participant suggests showing the asphalt temperature instead of the outside temperature, as the asphalt temperature is essential for the work they perform.	P11: “Yes, that is something I would have liked to see [temperature of the asphalt].”
Display water usage on a scale	Participant suggests showing water 'on a scale' in the virtual environment instead of 'low', 'medium' and 'high', as the current display does not resemble a real roller.	P16: “It says ‘high’, ‘low’ and such… well this is often shown on a scale. An that, well, was not the case here.”
Improve visibility of compacted asphalt	Participant suggests to further improve the visibility of compacted versus uncompacted asphalt.	P19: “Uhm… that you can see for example where on the asphalt you have been with the roller, and where you haven’t been, that you can see that better, that’s not good enough yet.”

Code Name	Definition	Real Example
Make asphalt ‘steam’ during rain	Participant suggests that steam should come off the asphalt when it rains, as this normally happens when water touches hot asphalt.	P19: “Well if it rains, and the asphalt is warm and uhm… then you’ll see steam.”
Only one paving machine	To reduce the large amount of asphalt that currently needs to be covered by one roller operator the participant suggests decreasing the amount of paving machines from two to one.	P18: “Then they should have… they should have done one [paving] machine and not two.”
Position the roller further away	Participant suggests that the roller should be placed further away from the asphalt, so it's either easier to steer the roller, or easier to choose which side you want to start.	P11: “I would have rather seen that the roller would have been positioned on the low side. Or that I would have had the room, so that I would have been able to start on the low side.”
Redundant suggestion	Participant makes a suggestion but the suggestion is already in the current build of the simulator (e.g. "I would like to see the joystick in the simulator as well").	P08: “But I would have liked it if the ‘joystick’ was also present uhm… in the simulator.”
Interference:		
Desire to play	Participant expresses a desire to try or test something because they want to see the impact within the virtual environment. In this case the situation is seen as a 'videogame'. Examples include participants who turn on the water not because this is an essential part of compacting asphalt but because 'they wanted to see what it looked like'.	P03: “Well uhm… I thought maybe it will go a little faster, the colours may change, I don’t know.”
Missing explanation	Participant did not further elaborate on why they made a certain decision. The explanation is missing. In some cases this is the fault of the researcher, who did not ask the right question at the time (e.g. "Why did you do x?").	P01: “I have to stop diagonally.”
Mistake by interviewer	Researcher made a mistake (e.g. incorrectly recalling something that the participant either did or did not do in the simulation).	Researcher: “I saw it once within the past three minutes that you stopped and you reversed immediately… most of the times…”

Code Name	Definition	Real Example
Struggle with virtual reality / controls	Participant states they were unable to do (or did not know how to do) 'something' in the virtual environment. This could be due to unfamiliarity with virtual reality or the controls (steering wheel & joystick). This includes doing 'something' incorrectly, driving off the asphalt for example if that was not intentional.	P13: “Well, nothing here [in the simulation], as I don’t really know how all of this works.”
Knowledge: Explicit		
Adjust roller speed due to rain	Participant adjusts the speed of their roller or wants to adjust the speed of their roller beyond the 'max' speed (as the roller was quite slow in comparison to real-life).	P10: “Well just continue rolling as quickly as possible behind the uhm.. [paving] machines so that everything is properly compacted.”
Adress existing stopping points	Participant addresses existing stop points or conveys the desire to place stop points accordingly (so they may be addressed at a later stage).	P16: “And then… it is an afterthought that the stopping point that you leave behind, that you address it at a later stage.”
Common roller speeds	Participants mentions roller speeds that are relevant during various circumstances (e.g. rain). This may also involve the effect that increased or decreased speeds have on the asphalt.	P20: “But normally you would go, about… four and a half, five.”
Compacting asphalt from low to high	Participant compacts asphalt from low to high and/or explains why they took this approach.	P11: “Then you start, and then it is always from low to high.”
Creating a daily seam	Participant mentions creating a 'daily seam' and/or actually made the decision to create a daily seam.	P19: “uhm… just like normal… you start with uhm… before you drive on to the asphalt with creating a seam.”
Detailed asphalt knowledge	Participant communicates deep knowledge of asphalt and how it behaves, this could relate to the thickness of layers, the way temperature impacts asphalt, etc.	P11: “You have an asphalt skeleton, uhm... and you roll over it and then you’re ordering stones but that means asphalt is a sponge. You compact it [the asphalt] at 160 degrees, but when it cools down the asphalt rises again.”
Effect of rain on asphalt	Participant describes the effect that the rain will have on the asphalt (e.g. drop in temperature, the asphalt starts floating, etc.).	P18: “If it rains harder, you have to be closer to it, because otherwise… well, then it [the asphalt] cools down too quickly.”
Manage asphalt temperature/compaction	Participant explains their overall plan, how they attempted to manage the	P11: “Well, you can see it here already, I was already getting a feeling of: “Hey, wait a

Code Name	Definition	Real Example
	temperature (or compaction) of the entire slab of asphalt. Even though this was very challenging as there was too much asphalt for one roller.	minute!" To the right, the high side [of the asphalt], it will take me way too long before I get there, because I'm servicing two [paving] machines on my own."
Planning a path with the roller	The participant describes the plan they had in mind when controlling the virtual roller, they either illustrate the path they wanted to take or the path they actually took. It could be that they took this path to work from 'low' to 'high' or they took this path to deal with stopping points, either way, conscious decisions were made about 'where to go' with the roller.	P04: "First a little to the left and then uhm… you push everything from the left to the right, so that the right side becomes higher."
Purpose of 'crab steering'	Participant explains the purpose of 'crab steering' why or how roller operators use this functionality.	P19: "The boys [colleagues], always have 'crab steering' turned on, what does that mean. It means that the front roll [of the roller] is aligned a little more to the left than the rear roll, so to speak."
Reduce the amount of stopping points	Participant conveys desire to reduce the amount of stopping points, most often this is relevant at the start of the simulation where there is only little asphalt to begin with (and as a result, you cannot move the roller very far).	P14: "The plan is, so to speak, to create as little stopping points as possible and still compact the entire work area."
Stopping diagonally on the asphalt	Participant either stops diagonally and/or explains why stopping diagonally is important.	P13: "You turn away and then you stop over here somewhere. You turn back, and in the next pass you'll be able to address the stopping point."
Waiting at the start of the simulation	Participant waits at the start of the simulation, this could be various reasons (to reduce stopping points, because pervious concrete is easily over compacted, or because there is simply not enough room yet).	P20: "Then I thought: well, they [paving machines] have to go forward a little, as I can hardly drive into the [paving] machine."
Water management	Participant makes use of the sprinklers or explains how they manage their water whilst operating the roller.	P14: "Well, firstly you turn on the machine [roller], then you turn on your water and then you determine how fast you need to drive."

Code Name	Definition	Real Example
When (not) to vibrate with the roller	Participant explains why they did or did not use the vibration functionality of the roller.	P18: "You cannot vibrate on pervious concrete otherwise you'll close it up and then… well, then it [the asphalt] is no longer open… and it's pervious concrete, then water can no longer pass through."
Working with pervious concrete	Participant reveals knowledge of pervious concrete that many explain why they performed certain behaviour.	P13: "And if you do small passes, you'll compact much more and with pervious concrete you are not supposed to compact it that much."
Knowledge: Implicit		
Adjust roller speed due to rain	Participant adjusts the speed of their roller or wants to adjust the speed of their roller beyond the 'max' speed (as the roller was quite slow in comparison to real-life).	P12: "No no… it was not… it was… it was… just like, well, now I have too, now I have to compact everything, I basically have length [to make roller passes]."
Reduce the amount of stopping points	Participant conveys desire to reduce the amount of stopping points, mostly relevant at the start of the simulation where there is only little asphalt to begin with (and as a result, you cannot move the roller very far).	P12: "I don't want to create too many stopping points. With rolling you try, you try to compact but you also want to flatten, compact and flatten…"
Stopping diagonally on the asphalt	Participant either stops diagonally and/or explains why stopping diagonally is important.	P19: "Yes, I steer away diagonally automatically, so that I roll over it [stopping point] in my next pass."
Waiting at the start of the simulation	Participant waits at the start of the simulation, this could be various reasons (to reduce stopping points, because ZOAB is easily over compacted, or because there is simply not enough room yet).	P18: "Now you can't go after the [paving] machine, you'll only make very short [roller] passes."
Knowledge: Missing		
Compacting asphalt from low to high	Participant is not aware that asphalt should be compacted from low to high. The low side of the asphalt was on the left side of the road in the simulation.	P05: "I thought, well, I'll start in the middle and then I'll first do the left side, then to the right. It probably would have been better if I started on the left".
Effect of rain on asphalt	Participant is not aware that rain severely impacts asphalt (e.g. rapid decrease in temperature).	P01: "And later on it started to rain. I thought well, that might actually be a good thing because otherwise it [the asphalt] gets too wet, I think."
Managing the speed of the roller	Participant either does not manage the speed or the	P02: "Well, maybe… a bit less speed…. [roll] a bit slower. On the one hand… well, now and

Code Name	Definition	Real Example
	roller or care about the speed of the roller.	then I went a little slower and sometimes a little faster. Well… actually, with rain I think it's easier to drive slower."
Planning a path with the roller	Participant does not have a plan of approach to compact all the asphalt in the best possible way, the paths that are taken are seemingly random, as the participant cannot explain the path that they took.	P05: "Because uhm… just naturally [changed direction].
Purpose of the sprinkler functionality	Participant does not understand what the purpose is of the sprinklers (they keep the rolls wet so asphalt does not stick to them).	P08: "No I have uhm.. I have only operated a roller at school. I have never worked with sprinklers before."
Purpose of the vibration functionality	Participant does not understand what the purpose is of the vibration functionality.	P09: "Well, I don't really know as we don't do that either here.... so I don't even know 100% for sure what it [vibrate functionality] is used for, I think I just forgot."
Responding to the rain	Participant does not respond to the rain in a meaningful way (e.g. the rain cools down the asphalt so the speed of the roller should be increased).	P07: "Nope, not really for me… for me nothing really changed."
Stopping diagonally on the asphalt.	Participant does not stop diagonally and/or is unaware that stopping diagonally is important.	P02: "Officially, you're not allowed to stop in a straight line. Well, officially?"
Participant: Nauseous		
Signs of nausea (potentially)	The participant either became nauseous or felt slightly off (e.g. strange feeling in stomach/head).	P18: "When you go backwards and then forwards again you get a strange… a strange twirl in your stomach."
Signs of Implicit Knowledge		
Unaware of Knowledge	Participant is not aware how or why they used a certain skill. In other words, the participant claims not to know how success was achieved.	"…"
Struggling to Articulate Knowledge	Participant struggles to articulate their knowledge, they may state that they find it difficult to explain themselves for example. Note: This must not be confused with a lack of knowledge.	P18: "Well, uh yes... that is difficult [to explain]. Well it is hard to express as this is something that you learn through time, because well... you can..., you cannot follow the [paving] machine right

Code Name	Definition	Real Example
		now, your roller passes will be way too short."
Reliance on Concrete Examples	Participant explains their knowledge through examples, they rely on practical examples to get their point across.	P12: "Well, alright, it's uhm... look if I... it depends on the weather you know, and whether it's a top layer... or whether I have to immediately be there because the layer is quite thin for example."
Descriptive Language	Participant vaguely explains their knowledge, using vague terminology like "something like that". It's clear the participant knows more, but the participant sticks to vague terminology.	"…"
Surprised Understanding	Participant becomes aware of knowledge they possess (they may even act surprised), implicit knowledge is suddenly made explicit (to a certain degree).	P18: "Well, I never really thought about it haha."
Use of Metaphors	Participant uses a metaphor to communicate their knowledge (e.g. to explain their reasoning or their goals).	"…"
Unconscious Automatism	Participant performed a certain action fully automatically, without any conscious deliberation. However, the participant is able to explain how and why they used the skill afterwards.	P19: "That is well… how you do it, that is automatism… nowadays."