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Review

Factors Influencing Attenuating Skill Decay in High-Risk Industries: A Scoping Review

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Abstract: The infrequent use of skills relevant in non-routine situations in highly automated and high-risk industries is a major safety issue. The infrequent use of skills can lead to skill decay. Research on skill decay has a long history, but not much is known about the relevant factors and refresher interventions to attenuate skill decay in highly automated environments. In the present study, a scoping review was conducted to determine whether the well-known factors in skill decay research are also relevant for complex cognitive skill decay and to identify refresher interventions that are deemed effective for attenuating decay. A scoping review aims at identifying, summarizing, and mapping the body of literature on a given topic. Searches in electronic databases, including PsycArticles, PsyINFO, and Psyndex, via EBSCOhost and Web of Science and Google Scholar were conducted, and documents were analyzed regarding the research question, which resulted in n = 58 studies. The findings demonstrate the relevance of task characteristics and method-related (cognitive-based, behavioral-based training) and person-related factors (e.g., cognitive ability, experience, motivation) to mitigate decay. Additionally, the results demonstrate that minor refresher interventions are effective at attenuating complex cognitive skill decay. Implications for industry and training providers that aim to implement training and refresher interventions to attenuate skill decay in high-risk industries are provided. Researchers may use the information about the influences of person- and method-related factors, task characteristics, and refresher interventions presented in this scoping review as a starting point to conduct further empirical research by taking skill acquisition, retention, and transfer into account.

Keywords: automation; non-routine situation; complex cognitive skill; skill acquisition; skill deterioration; skill decay; skill loss; skill transfer; refresher

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1. Introduction

Automation technology is implemented in companies of high-risk industries (e.g., energy supply, aviation, and maritime industries) for reasons such as ensuring safety and increasing economic benefits [1–4]. The implementation of automation technology in many organizational processes in high-risk industries has led to a change in the nature of work [5,6]. Due to highly automated environments, operators in high-risk industries are required to handle tasks that are increasingly complex and demand predominately cognitive skills [6]. Complex tasks (e.g., the start-up of a power plant or the navigation on a vessel's bridge) share defining attributes, such as consisting of multiple elements and sub-tasks that necessitate the integration and coordination of sequential steps [2]. In *routine* situations, automation technology supports the operator to execute complex tasks by gathering information and providing decision and action implementation options [7]. In these situations, the operator monitors, observes changes, and adjusts deviant processes [2]. The knowledge and skills required for monitoring, observing changes, and adjusting deviant processes are frequently applied [2,8]. The support of automation technology also means that only limited amounts of learned knowledge and skills in the human–automation interaction are used [9]. However, knowledge and skills that have been once learned must only be retrieved in the case of system failure (i.e., years after the initial training).

Although automation technology in high-risk industries is reliably, system failures occur [10,11]. To prevent catastrophic events, operators in high-risk industries should be prepared for and be able to respond to and recover from non-routine situations, including system failures [12]. For many of these situations, checklists and Standard Operation Procedures (SOPs) exist to guide operators' problem-solving behavior. Nevertheless, in the infrequent occurrences of non-routine situations, operators are required to transfer their knowledge and skills under time pressure [12]. The peculiarity of *non-routine* situations in highly automated and high-risk industries is that they are infrequent but can develop dynamically and are characterized by complexities resulting from the interconnectedness of system elements, which can result in opaqueness for the operator [13,14]. Non-routine situations in a chemical plant, such as disconnecting power, depressurizing, purging, and draining valves or preparing a plant for difficult weather conditions, can endanger the safety of operators if tasks are executed incorrectly or unsafely [8].

To give an example, to prepare for an infrequent maintenance activity, a coalescence separator and a caustic separator in a sulfuric acid alkylation plant were to be isolated and de-inventoried. During this work, only one valve was closed and isolated [8]. Although the control system indicated signs of a leak at the valve of the coalescence cutter, the leak remained undetected, allowing flammable liquid to aggregate and eventually leading to a flash fire, leaving the operator suffering from second-degree burns [8]. In another incident caused by Hurricane Harvey, operators at a chemical manufacturing facility were unable to keep flammable material below the temperature of self-accelerating decomposition, resulting in decomposition, release, and a fire, which posed a major health and safety risk for people 1.5 miles around the facility [15]. Although severe flooding had occurred at this facility in the past and the operators prepared for the hurricane, the serious danger constituted by the hurricane went unrecognized because none of the experienced operators could remember the severity of the past flooding [15].

These situations are infrequent, but the likelihood of extreme weather conditions is assumed to increase in the future [15], and require operators to transfer their knowledge and skills to increasingly complex situations that can develop dynamically.

Due to the infrequent occurrence of non-routine situations, the operator rarely applies all relevant skills and knowledge. Knowledge and skills that have been acquired once but are infrequently applied over longer non-use periods may be prone to decay. Skill decay is defined as the inability to retrieve formerly trained and acquired knowledge and skills after periods of non-use with a consequence of decreased performance [16,17]. As a result, operators experience difficulties in acting adequately when a non-routine situation arises. This is in line with the results from interviews with operators from a chemical plant [18]. The operators were asked about their knowledge and skills in non-routine situations, and one operator stated, "It's simply a question of the experience of the operators and of us supervisors planning our staff so that everyone does everything regularly so that the knowledge doesn't get lost. [...] For various reasons [...] it can happen that someone is not working for a longer period of time despite the good intentions, and then knowledge is lost." [18]. Consequently, the combination of knowledge and skill decay due to an infrequent application and occurrence of non-routine situations can endanger people's safety and reduce efficiency in high-risk organizations.

1.1. Complex Cognitive Skills

In companies of high-risk industries, which are defined as "organizations that are able to manage and sustain almost error-free performance, despite operating in hazardous conditions where the consequences of errors could be catastrophic" [19] (p. 1), operators have to apply knowledge and skills to detect a problem, make a diagnosis, and compensate and correct deviant processes [2]. In order to do so, operators need to be familiar with failures, identify subtle aspects of complex problems, and retrieve and integrate knowledge and skills that were once learned, but have been infrequently applied [12].

To acquire proficiency, considerable amounts of time and experience are required [20]. Different terms are deployed to describe proficiency, including competence, knowledge, and skill, depending on the focus of the research [21]. To obtain proficiency for a complex cognitive skill that is necessary for handling highly automated processes, learning proceeds through three stages: (1) declarative knowledge about the task being learned; (2) the learned and interpreted information results in proceduralized behavior, which describes a process in which essential knowledge elements are incorporated into new knowledge that no longer requires an effortful retrieval of declarative knowledge from the first stage [22]; (3) deliberate practice converts the learned knowledge into an automatized and compiled form [23]. The acquisition of complex cognitive skills through the three stages requires certain knowledge (e.g., declarative knowledge), skills (e.g., proceduralized behavior), and attitudes (e.g., willingness to invest the effort to continue with deliberate practice). In the remainder of the study, we therefore refer to complex cognitive skills, which include the necessary knowledge, skills, and attitudes to solve problems or tasks and promote transfer to novel situations [24]. Complex cognitive skills comprise psychomotor and predominantly cognitive processes, such as the sensory processing of multiple sources of information, diagnosis and inference, decision making, and the execution of actions [2,20,24]. They require considerable amounts of effort and time to acquire proficiency, individuals vary in their ability to master them (e.g., more or less time to achieve proficiency), and experienced and novice operators differ in execution of them qualitatively [20,24]. While skills required for more simple tasks, such as following a procedure with few action steps, seem to be easier to learn and more retentive, skills for cognitively complex tasks, such as monitoring, observing changes, making predictions based on system elements, and adjusting deviant processes, take time to acquire and might decay faster, depending on their characteristics [25,26].

1.2. Factors Influencing Skill Decay: Task, Method, and Person-Related Variables

According to studies in [16,27], the decay of skills is influenced by task-related, method-related, and person-related variables, which are already relevant in an early phase of skill acquisition but might also influence later phases of skill transfer or retention. *Task-related factors* can be described by their complexity (e.g., the number of action steps required and dynamicity) [28], and also concern—for instance, the frequency of occurrence of the situation (e.g., temporal transfer) or the novelty of the situation (e.g., adaptive transfer) [29]. *Method-related factors* refer to the training design or learning environment, which can be modified and can reduce skill decay [17,23]. These factors can be categorized into training or practice conditions and by the degree of overlearning [17]. Person-related factors that impact skill decay can be grouped into cognitive (e.g., general mental ability), attitudinal (e.g., motivation), and others (e.g., work experience) [16,27].

In conclusion, the ability to retain skills seems to be dependent on method-related and person-related factors, the complexity of the task, whether the task is novel (adaptive transfer), and whether it has not been performed for a long period of time (temporal transfer). Thus, to attenuate skill decay in non-routine situations and to promote a safe and efficient operator performance within a high-risk and highly automated environment, the consideration of potential influencing factors related to the task, the method, and the person is crucial.

1.3. Refresher Interventions to Attenuate Skill Decay and Study Aim

One way to attenuate skill decay is through refresher interventions. The objective of refresher interventions is the re-establishment of a specific skill level that was acquired during the initial training but has not been practiced for a long period of time [29]. High-risk industries that have to deal with highly automated environments counter skill decay with periodic refresher interventions/recurrent trainings, which are declared mandatory in some industries (including aviation—see, e.g., [30]; nuclear power plants—see, e.g., [31]; maritime; see, e.g., [32]) but not in others. The type of refresher intervention (e.g., practice, mental rehearsal, or test) can have a positive impact on skill retention, but its effectiveness is dependent on the type of task and skills required [33].

There are several reasons to revisit and update the skill decay literature with respect to complex cognitive tasks in high-risk industries. First, although a considerable amount of research exists that focuses on skill decay (see e.g., [16,27,34]), the last quantitative review [27] is from almost 10 years ago. As technological advancements rapidly increase, and the roles and tasks of operators change accordingly [35,36], a re-examination of the skill decay literature with a focus on highly automated environments in high-risk industries seems warranted. Second, recent reviews in the high-risk domain consider psychomotor tasks (e.g., life support procedures) (see [37–40]), which are not simply transferable to the complex cognitive skills necessary for handling highly automated processes. As a result, we can extract valuable information from the existing literature about skill decay, but the transferability to complex cognitive skills in high-risk and highly automated environments is restricted. Third, the research regarding refresher interventions considering complex cognitive tasks in high-risk environments is limited [33], and the type of refresher intervention for mitigating skill decay has not yet been considered in detail. Thus, we extend the literature on skill decay by focusing on complex cognitive tasks, refresher interventions, and the retention of skills over a longer period of time (temporal transfer) and for novel situations (adaptive transfer), which to our knowledge have not been previously reviewed.

A scoping review was conducted to summarize and disseminate the key concepts underlying the research on skill decay, complex cognitive tasks, and refresher interventions. Skill decay, complex cognitive tasks, and refresher interventions are researched in an interdisciplinary manner, but their commonality is their relevance to safety in high-risk industries. Scoping reviews are a relatively new approach to evidence synthesis and are particularly useful for collecting literature from different disciplines and combining it with new insights [41,42]. They are an ideal tool to determine the scope or coverage of a body of literature on a given topic and to outline the volume of literature and studies available [42]. The general purpose of conducting a scoping review is to identify and map the available evidence [42]. It is not limited to one discipline or domain (e.g., process control, training science, cognitive science or education, or instructional psychology) but covers the field comprehensively. The key question of this scoping review was: *How can skill decay in non-routine situations be attenuated within a high-risk, highly automated environment?*.

Therefore, in this publication, we

- Determine whether well-researched factors from the literature on skill decay (e.g., task, method, and person-related) are also relevant for attenuating complex cognitive skill decay for situations that are infrequent (temporal transfer) and/or novel (adaptive transfer) in companies in high-risk industries (connection 1, Figure 1);
- Identify refresher interventions that are deemed to be successful for retaining complex cognitive skills for infrequent situations (temporal transfer) and discuss whether they can promote handling of novel situations (adaptive transfer) in highly automated environments (connection 2, Figure 1).

As stated in [17,43], although acquisition, retention, and the transfer of skills are separate phenomena, to fully understand the potential impact of an intervention in the acquisition, retention, and transfer of complex cognitive skills, it is critical to consider each phenomenon in the analysis. The findings can be used by industry and training providers as resources to design training and refresher interventions based on a systematic approach that can help to mitigate complex cognitive skill decay in companies in high-risk industries. A systematic approach [44] means to first derive relevant factors for complex cognitive skill decay via analysis, and second, to compose a refresher strategy based on these findings (Figure 1).

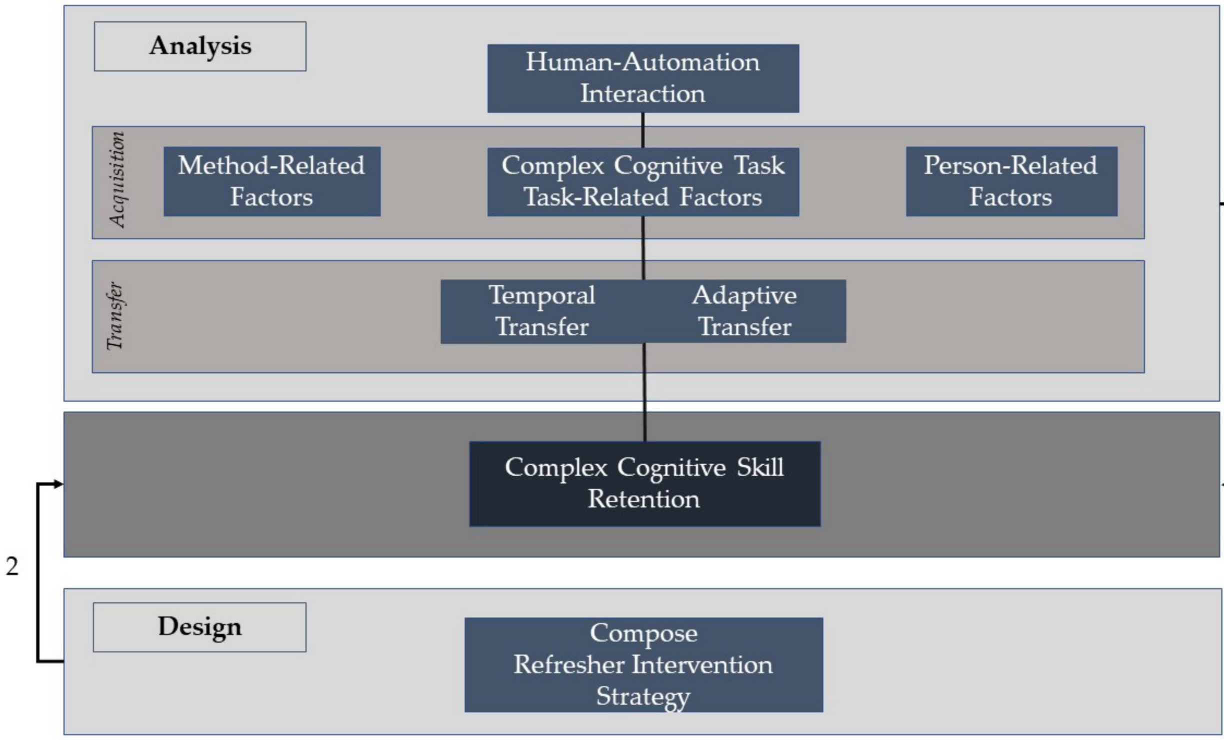

Figure 1. Graphical representation of the focuses and aims of this scoping review.

2. Methods

A scoping review was conducted that allowed for various study designs [45]. A methodological framework was chosen that shared processes with systematic reviews (e.g., the extraction of study results) [45]. Following the scoping review, a framework outlined in [45], five stages was implemented—(1) the identification of the research question (presented in the introduction); (2) the identification of relevant studies; (3) the selection of studies; (4) charting the data; (5) collating, summarizing, and reporting the results [45]. A breadth approach was employed. This means that the inclusion of studies was favored even if, for example, a construct within a study was not clearly specified, since the focus of a scoping review is on presenting and mapping the breadth of evidence [46].

2.1. Identification of Relevant Studies

In an initial search of the literature and databases, we identified the main concepts of the topics and compiled a list of relevant keywords (see Table 1). The documents of the original research, including peer-reviewed publications, conference proceedings, technical reports, and book chapters, were received from electronic databases, including PsycArticles, PsycINFO, and Psyndex, via EBSCOhost, and Web of Science and Google Scholar. The search of electronic sources took place from January to June 2021, and the search was not limited to a time span. Boolean operators were used for the following terms: refresher AND skill decay OR skill retention AND complex task/automation. To enhance the quality of the systematic review search terms, search strategy and keywords were discussed in the consultation with an experienced librarian in line with the scoping review standards advised in [45]. The searches in Google Scholar were conducted with the search terms "complex task" and "automation," separately (see Table 1). The term "automation" generated a great number of false positive results compared to the term "complex task," and was therefore not included in the following searches via EBSCOhost and Web of Science. The search terms for the systematic literature search are presented in Table 1. Additionally, reference lists and citations from key articles were screened to identify further relevant articles. The literature results were subsequently updated in July 2021.

Table 1. Search terms used for the systematic literature search in Google Scholar, Web of Science, and EBSCOhost.

Search Term #1		Search Term #2		Search Term #2		Search Term #3 [1]
refresher, refresher training, refresher course, refresher intervention	AND	skill decay, skill deterioration, skill loss, loss of expertise, loss of competence, knowledge decay, knowledge deterioration, knowledge loss	OR	skill retention, skill acquisition, skill maintenance, knowledge retention, knowledge acquisition, knowledge maintenance	AND	complex task, automated, automatized, automatised

[1] A separate search was conducted with automation as an alternative for search term #3.

2.2. Selecting Studies

Before the studies were selected for the final analysis, the terminology was defined, and inclusion and exclusion criteria were established. Studies were included if they related to complex cognitive tasks and skill or knowledge decay or retention, refresher training or intervention, and high-risk domains. Studies were excluded when they did not relate to high-risk domains or complex cognitive tasks (e.g., when they related to senso-motor and motor tasks), and when they did not relate to skill or knowledge decay or retention. In addition, studies that did not consider refresher training or interventions in high-risk domains for complex cognitive tasks were excluded. Definitions of complex cognitive tasks, skill decay/retention, refresher intervention, and high-risk industry used for the scoping review can be retrieved from Table 2.

Table 2. Definitions of key concepts for inclusion within the scoping review.

Definitions of Key Concepts	Reference
Complex cognitive task: Complex cognitive tasks are defined as consisting of multiple elements and part-tasks that include the integration and coordination of sequential steps in which attentional processes and knowledge elements are necessitated. With regard to this, skills are required with the majority of tasks involving cognitive processing relevant in non-routine situations.	[2]
Skill decay/retention: Skill decay is defined as the inability to retrieve formerly trained and acquired knowledge and skills after periods of non-use with a consequence of decreased performance. Retention is characterized by the ability to transfer formerly acquired skills to infrequently occurring situations.	[16,17]
Refresher intervention: Refresher interventions refer to all measures used to prevent skill decay in high-risk domains.	[29]
High-risk industry: High-risk industries are characterized by their dealing with challenging, disruptive events on a regular basis and the potential for dangerous situations. Examples of high-risk industries included, but were not limited to, the transport industry (e.g., aviation, shipping, rail transport), military, process industry (e.g., energy production), production industry (e.g., chemicals, pharmaceuticals), and medicine.	[13,19]

All types of study design were included. The studies had to be in English. Technical reports, articles, conference papers, and book chapters were included. The documents were first screened by title, abstract, and keywords, by applying the inclusion and exclusion criteria (see Figure 2). After removing duplicates and irrelevant documents that did not meet the inclusion criteria, the remaining documents were read fully, and access was requested when necessary. The remaining documents were analyzed against the research question in this review. Two researchers (out of a total of three researchers) independently applied the inclusion and exclusion criteria to 62% of the documents. The remaining documents were analyzed by one researcher. The documents were divided into the groups of relevant, irrelevant, and inconclusive. In cases of inconclusiveness, the inclusion of documents was discussed. Irrelevant documents were excluded from the final dissemination.

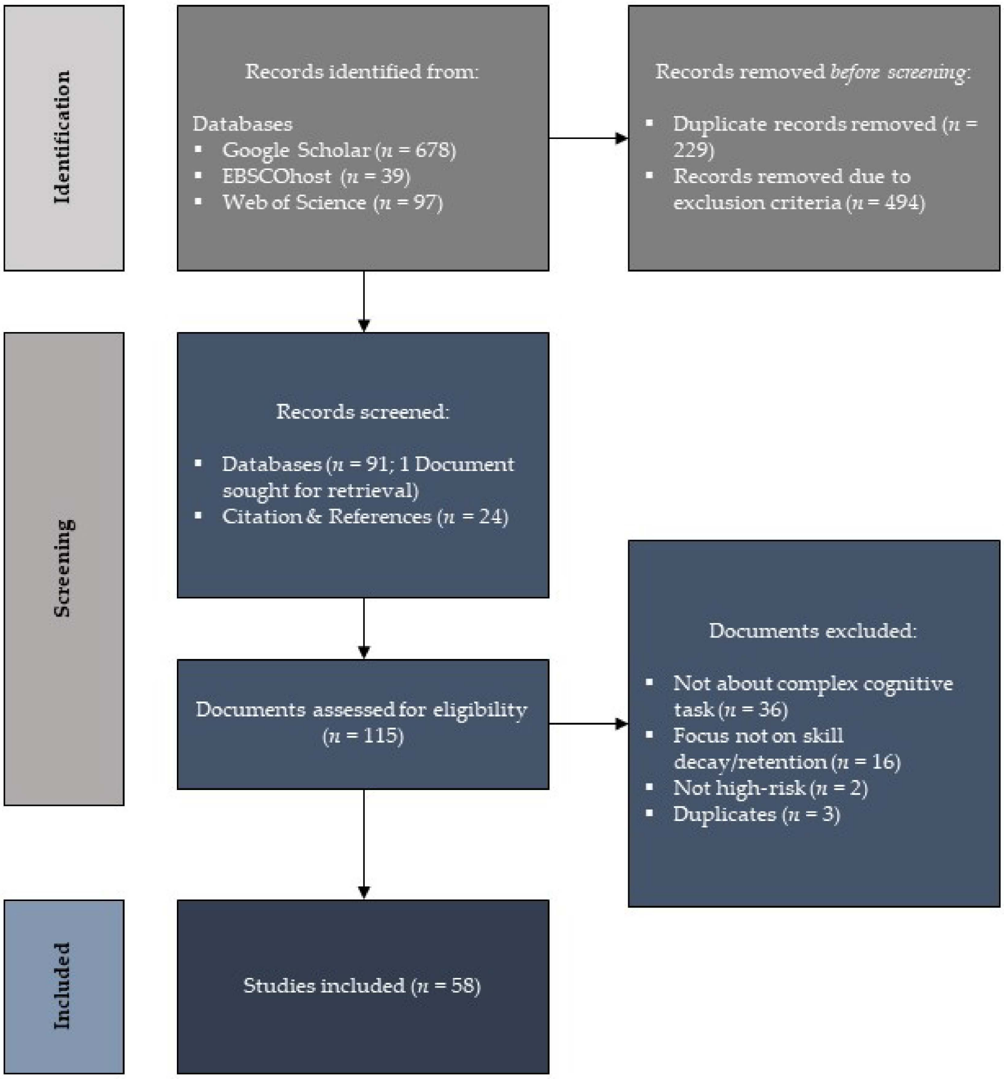

Figure 2. PRISMA flow diagram for systematic reviews.

2.3. Chartering the Data

A data-chartering form was developed to determine which variables to extract. Three researchers extracted the information of 62% of the documents independently. The data-chartering form consisted of descriptive variables (author, year of publication, study design, target group, and document type) and information about skill acquisition, transfer, retention, refresher interventions, and influencing factors, including task-related factors, initial training, and person-related factors. The data extracted were related to aspects regarding skill acquisition, transfer, and retention, and aspects describing the acquisition of complex cognitive skills through original learning. Information about task-related and other person-related factors that might have an influence on skill acquisition, decay, or transfer was extracted. For studies that contained refresher interventions, information about the refresher intervention and its influence on skill retention and/or skill transfer was reviewed. Additionally, key results, implications, and recommendations for future research were extracted.

2.4. Collating, Summarizing, and Reporting the Results

While focusing on disentangling the influencing factors and potential successful refresher interventions for attenuating the decay of skills needed in complex tasks in non-routine situations, descriptive and thematic analyses were applied to present the research findings in the following results section. The descriptive analysis provided an overview of the general data, and the thematic analysis was conducted to evaluate and categorize the research findings, that is, to identify the influencing factors that could be detrimental to complex cognitive skill retention and to identify the refresher interventions that could mitigate decay. Finally, research gaps were revealed regarding the attenuation of skill decay in high-risk, highly automated environments.

3. Results

The documents included in this review were published between 1972 and 2019 (n = 58). Most of these documents were articles (47%), and 62% of the included studies involved experiments (41% laboratory experiments, 21% field experiments; see Table 3). The assessed documents mostly had a process industry focus (28%) or a military focus (24%). The retention interval in the experiments ranged from less than 1 week to 156 weeks, and the mean was 17.03 weeks (SD = 27,90).

Table 3. Characteristics of documents included in this study (n = 58).

Document Characteristics	***n***	**%**
Type		
Technical report	17	29
Article	27	47
Conference paper	8	14
Book chapter	6	10
Industry		
Transport (aviation, maritime)	9	16
Military	14	24
Process	16	28
Production	4	7
Not specified (complex cognitive task)	15	26
Study Design		
Review	19	33
Laboratory experiment	24	41
Field experiment	12	21
Survey	2	3
Concept	1	2

The research resulted, in line with the research questions, in the identification of relevant factors that were shown to improve the retention and transfer of complex cognitive skills. Although studies have agreed that the greater the retention interval, the greater the skill decay [27,47–52], this also seems to be affected by other factors (e.g., task-related factors and level of skill in the first place), as presented in the following. It is noteworthy that the factors influencing complex cognitive skill decay or retention and transfer are interwoven and not necessarily mutually exclusive. The distinctions that are made between influencing factors are outlined in the following with the purpose of presenting the findings in a logical and coherent manner. In this scoping review, the findings are introduced under five general themes, which have been further subdivided into 17 subcategories. In the following, the themes that were derived from the documents are introduced respectively. Firstly, the factors influencing skill decay and/or transfer are presented, including task characteristics, person-related, and method-related factors. Secondly, refresher interventions are introduced, along with individual differences and their influences on skill decay and/or transfer. Thirdly, team skill decay is presented.

3.1. Relevant Factors during the Skill Acquisition Phase for Skill Retention and Transfer

One study [23] indicated the importance of skill acquisition for retention and transfer. Empirical research suggests that the better the acquisition phase and the better a task is proceduralized (e.g., essential knowledge elements are incorporated in new knowledge elements, which makes an effortful retrieval of declarative knowledge unnecessary), the more an individual can retain [53–56] or transfer to novel situations [57–60]. The retention or transfer is further influenced by task characteristics, person-related factors, and initial training.

3.1.1. Task Characteristics

The characteristics of complex tasks differ in their propensity to decay [47,51]. Tasks that require a considerable number of action steps that are performed in a specific required order and are accomplished in a timely manner, decay more rapidly [16,25,27,34,47,52,53,61–64]. These tasks require different cognitive abilities, are not simple to proceduralize, and consequently demand higher mental workloads [23,47]. In contrast, tasks that are performed more routinely or are more dynamic can be retained longer [46]. The task-characteristics that proved to be more prone to decay were closed-loop, procedural, discrete, and controlled processing tasks [16,25,27,34,47,52,61–64].

Task characteristics that were less prone to skill decay included open-looped, continuous, and automatic processing tasks [16,25,27,34,47,52–54,61–65]. However, there might be other factors that reduce or amplify the influences of task characteristics on complex cognitive skill retention, such as cognitive processing. The study presented in [27] concluded that the open-looped and continuous tasks lead to increased retention due to their higher component complexity, which requires deeper and more elaborative processing. Another study, presented in [61], suggested that these tasks can be better retained due to components that are better proceduralized (e.g., knowledge elements are incorporated into a new knowledge structure), for instance, because they can be practiced more often in the work environment. Further, studies presented in [29,66,67] demonstrated that declarative knowledge—knowledge about facts and information—can be retained well. Additionally, tasks that were highly organized, meaningful, and consistent across situations, and tasks that did not need to be accurately performed, deteriorated less [16,34,55,68,69].

In summary, how much and how rapidly skills that are needed for a complex cognitive task decay depend on several factors that do not need to be attributed to the characteristic of the task itself, but to the mental effort that is required to perform the task. Tasks that are not simple to proceduralize, that require considerable numbers of discrete cognitive processes, and that are not well organized are prone to skill decay, whereas tasks that are more meaningful, highly organized, and consistent across situations might reduce the mental effort [70], and thus might decrease the amount of skill decay (Table 4).

3.1.2. Person-Related Factors

Skill decay for a complex cognitive task also depends on person-related factors. A considerable number of studies have emerged in the last few decades that have concentrated on person-related factors regarding complex cognitive skill decay, focusing on cognitive factors (cognitive ability, general mental ability (GMA), retentivity, memory), experience, age, personality factors, and motivation.

All cognitive factors have been shown to be positively related with skill retention after periods of non-use, although there were differences in cognitive factors when it came to the transfer to novel situations. While retentivity and memory were indicated to be a supportive individual influence increasing skill retention after periods of non-use, they did not seem to facilitate adaptive transfer [72–74].

Overall, GMA was a relevant predictor of both temporal transfer and adaptive transfer [72]. Specifically, a combination of declarative knowledge and cognitive ability seemed to have a positive influence on adaptive transfer [75]. Although the research regarding cognitive ability and retention agrees that there is a positive relationship between both factors [49,54,55,69,75], the underlying causes that lead to this positive relationship are not yet clear. Individuals with higher cognitive abilities acquired more knowledge during the acquisition phase, but the decay of knowledge and skills seemed to be equal for both high- and low-ability individuals [25,75]. This indicates that different cognitive strategies are necessary for recalling important knowledge and skills after periods of non-use, and for adapting these skills to novel situations. As stated in [74], it does not seem sufficient to simply remember the facts and information about how a complex task needs to be performed for adapting skills to a novel situation. Indeed, it may be the case that one needs to be able to understand the novel task, and combine and develop new strategies, which demands deeper elaborative processing.

Table 4. Task characteristics and their expected impacts on skill decay.

Task Characteristic	Description	Expected Impact on Skill Decay
Closed-looped, discrete	Tasks that consist of fixed sequences of operator actions involving (timed) coordinated responses with a definite beginning and end, for instance, the start-up of a power plant, following safety procedures [16]	Supports skill decay [25,27,34,53,63,64,71]
Unorganized, inconsistent, less meaningful	Tasks that incorporate steps that do not logically follow each other, and which demand controlled mental processing [33]	Supports skill decay [64,68]
Open-looped, continuous	Tasks that require continuous operator responses that do not have a definite beginning and end, for instance, problem-solving, making judgements [16]	Reduces skill decay [27,60,63]
Highly organized, consistent, meaningful	Tasks that incorporate steps that follow a logical order, which promotes a faster and higher order mental processing of the task [33]	Reduces skill decay [16,55,61,69,70]

The demographic factor of age did not influence skill decay directly, but could potentially influence decay indirectly through stress and work experience [53,63]. It was stated that there are benefits of higher age in terms of the acquisition of experience through tenure, but the information processing ability under stress declined with age, which could hamper skill retention [63].

Experience has been found to have positive influences on skill retention [49,55,65,76] and transfer [55]. Although experience might lead to more routinized performance, it cannot counteract skill decay completely [76]. Out of the personality factors, only conscientiousness and openness to experience have been investigated. It was found that conscientiousness did not relate to skill decay and that openness to experience had a negative influence on skill transfer [75]. It was argued that when individuals who were open to experience were confronted with a novel situation, they were likely to try out different approaches that are not necessarily promising. Further, individuals who were highly deliberate, orderly, and dutiful, which are characteristics of the personality trait of conscientiousness, were less able to adapt their skills to different situations [75]. Individual factors that proved to be positive for decreasing skill decay were achievement orientation [63] and self-efficacy [75], through their motivational properties and the desire to sustain professional competence [63,75].

In summary, among the person-related factors, general mental ability and experience proved to be supportive factors for both temporal and adaptive transfer, although decay cannot be mitigated completely. Retentivity, memory, and cognitive ability impacted skill retention positively but did not seem to have an influence on the transfer to novel situations. The individual achievement orientation and self-efficacy were relevant motivational aspects that increased skill acquisition and retention through maintaining effort during training sessions.

3.1.3. Initial Training: Method-Related Factors

Complex cognitive skills necessary for operators handling automation technology are acquired through three stages, namely, obtaining declarative task knowledge, applying the learned and interpreted information in the form of behavior, and deliberately practicing the learned knowledge in a proceduralized and compiled form [23]. There are different training methods that help to acquire these complex cognitive skills and increase retention. Several studies have focused on cognitive-based methods (e.g., knowledge organization and mental models), behavior-based methods (compilation, proceduralization), and additional beneficial factors that influence skill retention (e.g., fidelity, brain stimulation, and cognitive aids). An overview of methods for initial training to acquire complex cognitive skills and their influences on skill retention and transfer is given in Table 5.

Table 5. Initial training: method-related factors for complex cognitive tasks and their impacts on temporal and adaptive transfer.

Intervention	Principles	Expected Impact on Temporal and Adaptive Transfer
Behavioral		
Proceduralized processing		
Overlearning Authors: [77]	Determined fixed amount of time or acquisition level after skill mastery was reached.	Temporal transfer: improved Adaptive transfer: no information
Massed practice, drill and practiceAuthors: [57,78]	Completion of a set of tasks in extensive rehearsal sessions.	Temporal transfer: improved Adaptive transfer: no effect
Part-whole task practice Authors: [60,61]	Training components of a complex task to acquire proceduralization of the skill and later integration into the whole task.	Temporal transfer: improved Adaptive transfer: improved
Compilation		
Distributed practice/spacing Authors: [79]	Inserting a time-interval between the rehearsal of a task during skill acquisition.	Temporal transfer: improved Adaptive transfer: no information available
Peer tutoring Authors: [25]	Individuals teaching each other.	Temporal transfer: improved Adaptive transfer: no information available
Dyad training Authors: [80,81]	Individuals perform each half of a complex task in harmony with a partner actively performing the other half of a complex task.	Temporal transfer: no effect Adaptive transfer: no effect
Error training Authors: [78]	Errors are experienced, consequences of errors perceived, and feedback provided.	Temporal transfer: improved Adaptive transfer: improved
Cognitive		
Elaborative processing		
Emphasis-shift training Authors: [57]	Introduction of changes to highlighted components of a task for reprioritization while keeping the whole task intact.	Temporal transfer: improved Adaptive transfer: improved
Emphasis-shift training and situation awareness training Authors: [57]	Introduction of changes to highlighted components of a task for reprioritization while keeping the whole task intact in combination with random "freezing" of a task with questions and debriefing.	Temporal transfer: improved Adaptive transfer: improved
System-based training Authors: [82]	Encouraging to understand the interactions and relationships between system components.	Temporal transfer: improved Adaptive transfer: improved

Table 5. *Cont.*

Intervention	Principles	Expected Impact on Temporal and Adaptive Transfer
Systemic information training Authors: [58]	Information about the system of a plant given while participants have to develop their own diagnostic strategy.	Temporal transfer: improved Adaptive transfer: improved
Procedure-based training (and error heuristic) Authors: [78,82]	Emphasis on following procedures for fault identification and management (and advice to handle typical errors).	Temporal transfer: improved Adaptive transfer: improved

Note. Temporal transfer = skills can be retained for longer periods of time; adaptive transfer = skills can be transferred to novel situations.

Behavior-Based Methods

To become more experienced and create routines, behavior-based methods can be applied to promote proceduralized processing by overlearning, massed practice, drilling and practice, or part–whole training. While well-acquired task components resulted in proceduralized skills, which increased the long-term retention of task components [23,61,70], these proceduralized skills did not necessarily result in skill transfer to novel situations [60]. Individual differences influenced the training outcomes in terms of the extent to which an individual was able to acquire a complex cognitive skill. Individuals with higher GMA and those who were less conscientious benefitted most from methods that were well-structured, such as drills and practice, but not from those that encouraged self-learning strategies [83].

Further, discordance existed regarding the required amount of practice. Some results indicated that more practice was not necessarily better [59,61,70], whereas others suggested that more practice was better [53–56,71]. The amount of practice necessary seems dependent on the complexity of the task and the skill acquisition state in which an individual is situated. For individuals who were inexperienced in performing a complex cognitive task, behavior-based approaches to acquire a routine were beneficial, whereas more experienced individuals benefitted more from deeper cognitive processing about the interrelationships of the task [23,83].

Other behavior-based methods contained the strategy of compilation, which is purposed to speed up and make performances more accurate [84]. This can be accomplished by distributed training over several time-points, the training of dyads, peer-tutoring, or error training. Past research acknowledged that distributed training over several time-points resulted in minimal decay of a cognitively complex skill after a long-term non-use period [23,25]. Further, those who undertook dyad training, in which each individual of the dyad acquired half of the skills needed for a complex task separately, but could train both halves together, did not differ in their performance from those who were trained individually after a non-use period [80,81]. Tutors who taught other individuals in peer-tutoring on a complex task could retain more skills in the long-term compared to individuals who did not teach others [25,54]. It was argued that these methods provided individuals with more time to process complex cognitive tasks and that individuals were able to form effective cognitive strategies [54,81].

Cognitive-Based Methods

Cognitive-based methods emphasize the dynamic processes of skill acquisition organization and application [84], and include training in which individuals learn information about the task elements, rules, and interrelationships of a system. When individuals were trained to understand the relationships and interactions between different system components, performance was accurate after the non-use period and could even be transferred to novel situations [57,58,82]. A study presented in [58] found that these results could be increased when individuals were able to apply their own strategies for transferring the skills to practiced and novel situations. These cognitive-based approaches led to an increase in mental model forming and higher levels of knowledge, which in turn increased skill retention. When individuals were inexperienced in handling complex tasks, it was suggested that a behavior-based approach (e.g., overlearning) first be provided and then a cognitive-based approach to minimize cognitive overload [57].

In summary, depending on the level of experience and proficiency, different training methods should be applied to increase the retention of complex cognitive skills. While less experienced individuals who need to proceduralize skills benefitted more from behavior-based methods, including overlearning, experienced individuals who have the complex cognitive skills proceduralized profit more from cognitive-based methods, including system-based training.

Facilitating Factors for the Initial Training

Other facilitating factors that influenced the acquisition and retention of a skill were the provision of feedback, brain stimulation, cognitive aids (e.g., gaze guiding and memory aids), and fidelity. The provision of feedback seemed to have a positive influence by increasing the individual's motivation and improving the accuracy of performance [55,61]. It was indicated that brain stimulation reduced the cognitive load during the acquisition of a complex cognitive skill, and thus also reduced the cognitive load during the retention of the skill [85]. The implementation of gaze-guiding, a tool that supports the individual to direct her/his attention to relevant system information, and which was presented for the retention of a complex cognitive skill, facilitated performance via an increased production rate and decreased error rate [86,87], but skill deterioration could not be mitigated [88]. Memory aids were used to improve the connections between task elements of a complex task that would otherwise be more easily forgotten due to a weakened connection [61,70].

The physical fidelity of the equipment proved to have less influence on the retention of complex cognitive skills [55,56,71]. A high simulator fidelity helped to give trainees intensive practice, which increased stress resistance under periods of high demand [69], and to train system dynamics [89]. However, for the retention of complex cognitive skills, it seemed crucial that the equipment had cognitive fidelity rather than physical fidelity. This means that the trainees rather needed to attach meaning (e.g., the way tasks work and how to interact) to the training in relation to the practical context [55,56].

In summary, the provision of feedback, brain stimulation, cognitive aids, and cognitive fidelity further increases the acquisition of a complex cognitive skill, and consequently retention. Less is known about how these factors might impact the transfer of complex cognitive skills to novel situations.

3.2. Effectiveness of Refresher Interventions

A number of recent studies exist that focused on the effectiveness of different refresher interventions [29,33,62,66,74,76,90–93]. Refresher interventions could be categorized by their focus on cognitive, behavior, and test effect (see Table 6). The studies presented in [47,52] suggested that even a minor refresher intervention was helpful to attenuate decay in several skill areas.

Table 6. Refresher interventions for complex cognitive tasks and their impacts on temporal and adaptive transfer.

Intervention	Principles	Expected Impact on Temporal and Adaptive Transfer
Behavioral		
Practical rehearsal/skill proceduralization		
Practice Authors: [33,52,62,66,73,76,90,91,93]	Execution of the original task for a specific amount of time or reaching a specific performance level.	Temporal transfer: improved Adaptive transfer: improved

Table 6. *Cont.*

Intervention	Principles	Expected Impact on Temporal and Adaptive Transfer
Observational rehearsal Authors: [94]	Watch an online training video with an ineffective and effective performance, respectively.	Temporal transfer: no effect Adaptive transfer: improved
Test effect		
Skill test Authors: [66,76,90]	Make individuals highly responsible to the task by indicating that other people are highly dependent on their performance outcome.	Temporal transfer: improved Adaptive transfer: no information available
Knowledge test Authors: [66,76,90]	Recall steps of the procedure without cues and give reasons for erroneous procedure.	Temporal transfer: improved Adaptive transfer: no information available
Cognitive		
Theoretical rehearsal/mental practice		
Symbolic rehearsal/reproduction practice Authors: [66,74,76,90–92,95]	Recall the sequence of steps, arrange steps in the correct order, find errors from a presented procedure, provide reasons for erroneous procedure.	Temporal transfer: improved Adaptive transfer: improved
Symbolic rehearsal with added human-computer interaction (HCI) Authors: [74]	Recall the sequence of steps, arrange steps in the correct order, find errors from a presented procedure, provide reasons for erroneous procedure. Rehearse facts and labels about the operating system and mark different locations in a graphic.	Temporal transfer: improved Adaptive transfer: no information available
Extended symbolic rehearsal, blind practice Authors: [90,92]	Recall system interface, recall the operational function of the system.	Temporal transfer: improved Adaptive transfer: no information available
Mental rehearsal Authors: [48]	Pre-brief of procedures prior to completing the task.	Temporal transfer: improved Adaptive transfer: no information available

Note. Temporal transfer = skills can be retained for longer periods of time; adaptive transfer = skills can be transferred to novel situations.

The cognitive-based refresher was aimed at the active recall of declarative and procedural knowledge. In these refresher interventions, individuals were asked to recall procedures (procedural knowledge test), perform a task mentally (e.g., symbolic rehearsal, or an extended symbolic rehearsal), or to verbally recall steps from a procedure (e.g., pre-briefing). Whereas knowledge was retained, there was an overall moderate skill decay when cognitive-based refresher interventions were conducted [66]. This suggests that some parts of skill decay can be retarded by cognitive-based refresher interventions, but that skills still decline significantly [48,53].

Behavior-based interventions included observations, practice, and skill testing. During a retention interval, individuals in the study presented in [96] watched a video during a period of non-practice, with both effective and ineffective behaviors for accomplishing a complex task. The results indicated that watching the videos did not impact skill decay, whereas the impact on the transfer to a novel situation was positive. Thus, individuals were able to transfer skill performance to a novel situation by watching a video about effective and ineffective behavior. Studies focusing on practice as a behavior-based refresher intervention indicated an overall positive effect on the retention of complex cognitive skills [47,62,64,66,90–92]. It has been indicated that practice lowers stress in a procedural task and enhances the speed and improves the correct execution of accomplishing a complex task [93]. Interestingly, in a research project presented in [62], the results revealed that a skill that was simple, standardized, and with which operators had the most experience, decayed the most, despite the practice refresher intervention. It remained unclear why this skill area decayed more than other more complex skills in spite of the practice refresher intervention. Similar results have been found in other studies that showed that some skill areas remain almost intact (e.g., declarative knowledge) and others decline rapidly [67,97]. Thus, practice has many positive effects on the retention of some skill areas by increasing the retrieval strength, but other skill areas might still decay [62].

As is the case for the original training methods used for skill acquisition, individuals benefit differently from refresher interventions. A study presented in [74], which investigated different rehearsal designs in combination with individual differences, found that, firstly, individuals with higher retentivity could retain significantly more of a complex cognitive task compared to low-retentivity individuals. Secondly, individuals with higher retentivity benefitted the most from a symbolic rehearsal solely compared to an additionally implemented extended human–computer interaction rehearsal design [74]. Even a small amount of low-fidelity refresher intervention seemed effective in mitigating the severity of the decay.

In summary, both cognitive-based and behavioral-based approaches have positive effects on parts of skill retention, although skill decay cannot be attenuated completely. The cognitive-based approaches and behavioral-based approaches should be based on the skill level of the individual. It further seems that cognitive structures (high or low retentivity) that are in line with the intervention outcome (cognitive/behavioral) should be considered when selecting an intervention.

3.3. Team Skill Decay

The majority of skill decay literature in this scoping review dealt with individual skill decay. Additionally, the concept of team skill decay emerged as a key concept when considering non-routine situations in high-risk and highly automated environments. As with individual skill decay, the retention of a task is influenced by the number of action steps and the number of specialized skills and cognitive demands [98]. The difference is that the retention of the collective task also depends on the interdependence among team members, the amount of coordination required, and the quality of information exchange [98]. Consequently, when team members were less able to coordinate and exchange information, despite the task being highly interdependent, team skill decay was more likely to occur [98]. This was confirmed in a study that aimed to investigate whether and how team skill decay is different from individual skill decay [98]. The result was that team skills indeed decay over time, but this loss could not be completely attributed to the individual skill decay. This means that team skill decay was not only caused by a loss of individual skills, but also by a loss of team interaction skills (team coordination and team situational awareness) [99].

As with individual skill acquisition, team skill acquisition can be increased with initial training methods. These methods focus on training team members in each other's tasks in order to build awareness of individual capabilities. In line with cognitive-based approaches for individual skill acquisition, team skill acquisition training should also force the elaboration of cognitive structures by making contextual inferences and distributing the practice [98]. When comparing different training methods (*cross-training*: learning about the information requirements of other team members, *procedural based training*: learning written instructions about communication rules (who talks to whom about what and when), *perturbed training*: presenting deliberate changes within the simulation to block any routine coordination), it was found that perturbed training led to different coordination dynamics and also produced the highest performing teams after a non-practice period [100]. Interestingly, team compositions that were different in the acquisition and retention phases had greater knowledge accuracy, and team processes improved after a period of non-use [100].

In summary, it can be stated that team skill decay cannot be solely based on individual skill decay and that the execution of coordinative and communicative processes, and interdependence, play additional roles. Counterintuitively, situational and team composition changes resulted in increased team performance in the retention phase. However, no studies were found that focused on refresher interventions at a team level regarding cognitively complex tasks.

4. Discussion

The aim of this scoping review was to identify factors that have an influence on skill decay in complex cognitive tasks and to identify refresher interventions that are deemed to be successful for retaining complex cognitive skills relevant in high-risk and highly automated environments. It was demonstrated that the level of skill acquisition has a significant influence on the retention of complex cognitive skills that are not applied for long periods (temporal transfer) and on effectiveness in novel situations (adaptive transfer). Additionally, the research revealed that any refresher intervention is better than no refresher intervention to attenuate skill decay.

The level of skill acquisition and thus influence on skill retention are affected by person-related factors, method-related factors, and task characteristics. The influence of task characteristics on decay can be lessened depending on how well the task is cognitively organized, how meaningful it is, and whether the task elements are consistent across situations [16,55,61,69,70].

Cognitive-based training methods help individuals to form consistent and organized information about task elements, rules, and interrelationships of a system. However, it could be demonstrated that an individual needs some level of proceduralized performance of task components before learning the interrelationships, dynamics, and heuristics of a system [57].

For refreshing skills, even minor refresher interventions can have a positive effect on skill retention [90]. This can be explained by the fact that parts of complex cognitive skills (e.g., declarative knowledge) that were once required seem not to decay rapidly [52,62,89]. It could be demonstrated that observational rehearsal and cognitive rehearsal, which can be time- and cost-effective, are able to help individuals to not only retain the skills temporally but also to adapt these skills to novel situations [66,94]. Further, in line with method-related factors, inexperienced individuals might benefit more from practice than from cognitive interventions [90]. Individual differences (e.g., cognitive factors, personality factors, and experience) might determine the effectiveness of a refresher intervention on the retention and reacquisition of a cognitively complex skill. When composing a refresher intervention, it is necessary to know in which acquisition stage the individual is situated, and what intervention fits the individual's preferences.

The factors derived from the studies above can be adapted by vocational training departments in high-risk industries to design more impactful initial training and refresher interventions that yield greater retention of cognitively complex skills. Based on these results, Figure 3 represents recommendations for attenuating skill decay for inexperienced and experienced operators during the acquisition and retention phases.

For inexperienced operators learning a complex cognitive task, initial practice-based and demonstration-based training is recommended. As inexperienced operators need to construct domain-specific knowledge and need to gather experience to form knowledge elements into proceduralized performance, proceduralized processing techniques should be already integrated into the initial training.

Second, the set of facts and information needs to be compiled into one element to reduce an effortful retrieval, which can be promoted by compilation techniques, such as distributed training, dyad training, and peer-tutoring. Finally, the acquired complex cognitive skills need to be tuned and a gradual process of acceleration must be supported (skill becomes automatized), which can be promoted by cognitive elaboration, including system information training and emphasis-shift training. These training methods help operators put deliberate effort into aspects of their performance and deepen their understanding of, for example, difficult and complex problems [101]. The fine-tuning and process of accelerating a complex cognitive skill are important to reduce the mental workload during non-routine situations and consequently reduce erroneous operator actions. Factors including the provision of feedback, gaze guiding, and memory aids can facilitate the learning effect during the acquisition of the complex cognitive skill.

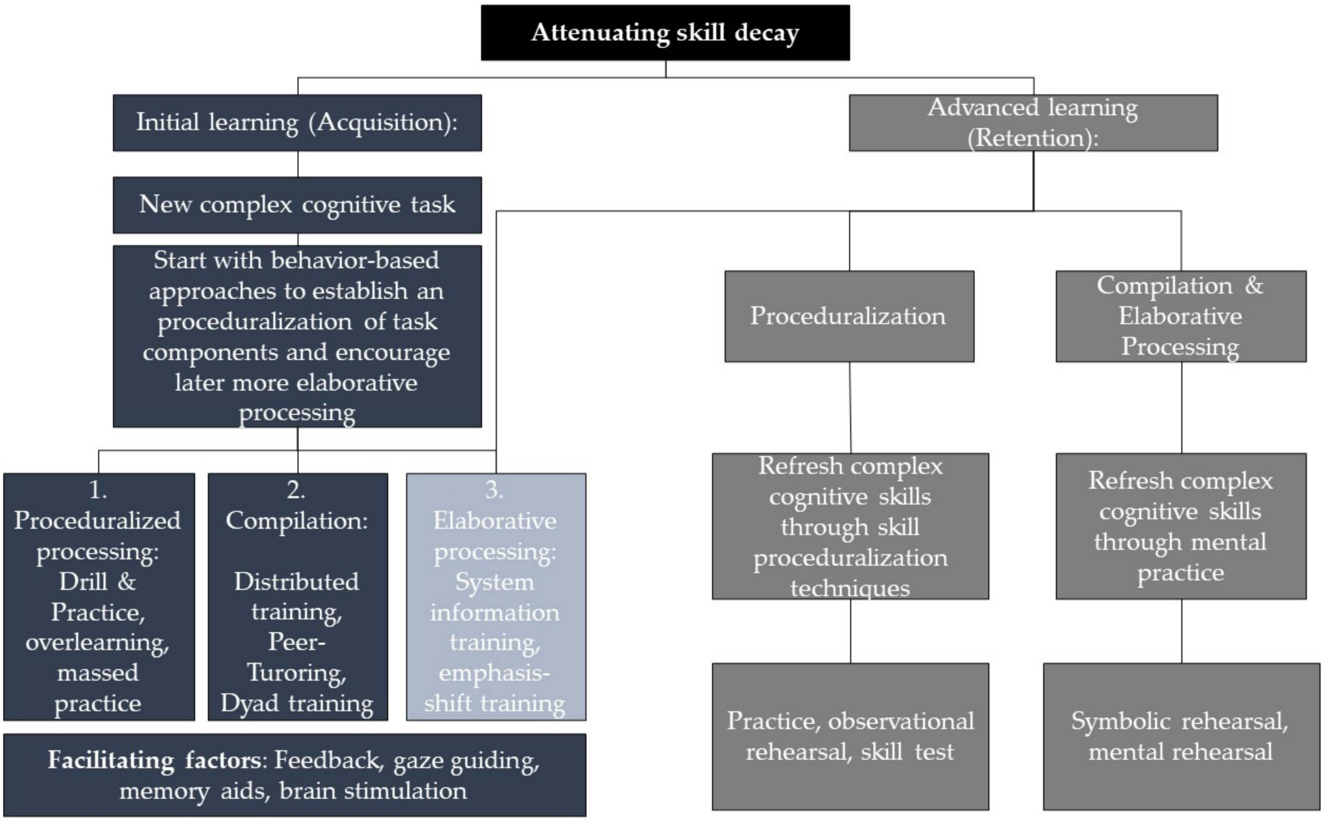

Figure 3. Recommendations for attenuating skill decay.

Experienced operators confronted with a new complex cognitive skill are best supported by cognitive-based methods, because it can be assumed that parts of a complex cognitive skill are already proceduralized. With cognitive-based approaches, the rules, interrelationships, and dynamics of a system can be trained, and deeper, more elaborative processing can be evoked, which results in increased retention. Conversely, operators who lack the essential knowledge elements to understand system dynamics can be overwhelmed when training cognitive-based methods. It is advisable to test whether experienced operators have the necessary skills for executing the new complex cognitive task or whether skills need to be refreshed. Based on the type of complex cognitive skill that needs a refreshment, one can distinguish between proceduralization techniques and compilation and elaborative processing techniques. The latter can support the types of skills that are required for the mental accomplishment of the tasks, including the application of understanding interrelationships and dynamics of a system, whereas proceduralization techniques can support the types of skills that are required for the behavioral execution to accomplish the task. Additionally, individual differences, including retentivity, should be considered; operators with higher retentivity should be provided with a cognitive-based refresher intervention, including mental practice, whereas operators with lower retentivity benefit more from proceduralization techniques.

While the findings in this study offer important information about the factors influencing skill retention and refresher interventions, there are limitations that need to be addressed in future research. As stated by [43,81], skill acquisition, retention, and transfer are different phenomena but should be treated together when research aims to understand the relationships and influences that might affect them. While a large number of studies have focused on skill acquisition and temporal transfer of a skill (e.g., retention), only a small number of studies have also taken adaptive transfer into account. Further, there is still a criterion problem regarding the achievement of mastery. For instance, mastery can be achieved by a predetermined set of correct trials performing a task or by training individuals for a certain amount of time [81]. Thus, for measuring skill decay, it remains unclear when skill acquisition should end and the non-use period should begin. Additionally, several studies have investigated the influences of individual differences on skill decay, and valuable insights could be gained with respect to cognitive ability. However, it was still not possible to draw conclusions about the processes of cognitive structures or learning preferences leading to a greater or lesser decay after periods of non-use. Another limitation refers to the definition of complex cognitive tasks. While this study established clear criteria for the inclusion of studies regarding complex cognitive skills, it remained difficult to exclude or include studies based on these criteria. Definitions of complex tasks in the studies varied greatly. For instance, complex tasks ranged from following procedures and using psychomotor and cognitive skills, to accomplishing dual tasks and mainly using cognitively complex skills. Further, although only original studies were included in the literature search, some documents analyzed probably came from the same sources, for instance [79,96]. The differences were related to the time studied, the general research objective, and thus, a slightly different representation of the results. This led to potential overlapping of information to an extent that we cannot determine. According to the applied breadth approach, the inclusion of studies was favored, although complex tasks were not always explicitly defined within the literature. Thus, their applicability to a highly automated environment in high-risk industries is limited. Further, attitudes and team skill decay were not often considered in relation to complex cognitive skill acquisition, transfer, and retention in high-risk industries, which indicates a promising research area.

Future studies should focus on the above-discussed limitations by establishing theoretical foundations regarding the criterion problem of mastery and complex tasks concerning complex cognitive skill decay. Additionally, more research is needed to unveil individual differences (e.g., cognitive processing structures and learning styles) and to optimize initial training and refresher interventions regarding skill acquisition, retention, and transfer. The findings from these future studies could help researchers and practitioners alike. For researchers, uniform application of definitions could lead to more comparable study results. For practitioners, future findings could increase the ability to design more impactful training and refresher interventions to prevent complex cognitive skill decay in highly automated environments of high-risk industries.

5. Conclusions

The inability to retain skills for non-routine situations remains a major challenge for companies in high-risk industries. In these industries, individuals are handling complex technologies, which in normal situations work reliably. Likewise, individuals may not need to apply formerly acquired skill components for months or years and can become unable to act when confronted with technological failures, which can consequently lead to the escalation of a situation.

In our review, we examined the broader literature concerning factors relevant to skill acquisition and decay in relation to complex cognitive tasks in high-risk industries. Several relevant factors were unveiled and could be categorized into training methods, including system-based training or drills and practice; person-related factors (e.g., cognitive ability and experience); task-related characteristics; refresher interventions, for instance, mental rehearsal or practice; and team skill decay. Training providers and organizations of high-risk industries are provided with valuable insights which can be integrated into the design of training for acquiring complex cognitive skills and refresher interventions to mitigate decay.

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