Fidelity in Simulation-based Training in Diverse Professions: A Proposed Taxonomy

by

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ABSTRACT

This paper examines the concept of fidelity within simulation-based training (SBT) across multiple professional fields. This paper: develops a taxonomy to classify tasks trained via SBT across diverse professional fields; develops a taxonomy to classify the elements of fidelity within SBT; and examines the relationship between fidelity in SBT and skills transfer to the operational environment (transfer effectiveness). It was found that increased fidelity in SBT does not always result in increased transfer effectiveness and that the relationship between transfer effectiveness and fidelity is nuanced.

Keywords: simulation; simulator; fidelity; training; transfer.

AUTHOR'S DECLARATION

I hereby declare that this project consists of original work of which I have authored. This is a true copy of the work, including any required final revisions, as accepted by my committee.

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DEDICATION

This work is dedicated first of all to my wife, Dawne Jones without whose support my head would have surely imploded; to my children Garret, Kaylee and Nate for motivating me; and to Dr. William Hunter for his patient guidance and tolerance of my sense of humour.

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Skills Transfer Effectiveness and Fidelity in Simulation-Based Training

The goal of this paper is to investigate the relationship, if any, between the fidelity of simulation-based training and the effectiveness of skills transfer from simulation-based training to the operational environment. This potential relationship is important because as a general rule the cost of a simulation is proportional to its fidelity (Miller, 1954). A clear understanding of the potential relationship between fidelity and transfer effectiveness will enable designers of simulation-based training to allocate resources to the aspects and elements of fidelity which produce the greatest returns in transfer effectiveness. Before a clear picture of this potential relationship can be formed, a framework for its investigation must be built. This framework is outlined below and is used to inform the research questions for this paper.

Many professional fields use simulation-based training. As will be shown later in this paper, each professional field has developed its own nomenclature and concepts for simulation-based training. This diversity of nomenclature and concepts has proven to be a barrier to the free flow of information among those who study simulation-based training. The hope is that the conclusions of this paper could serve as a common lexicon to help overcome this barrier. With this objective in mind, the author made the assumption that in order to have the widest practicable applicability, the conclusions of this paper must be based on examples from across the widest practicable spectrum. This means that the first element of the framework is to determine what professional fields use simulation-based training and what skills are trained with it. This requirement is the basis for research question one.

The second element of the framework is to build a functional definition of fidelity. Fidelity is generally regarded as how well a simulation resembles its referent system (Miller, 1954). This general definition lacks the specificity to be functionally useful for this paper. Compounding this situation is the fact that most professional fields view simulation fidelity differently. These two problems are addressed by reconciling the various views of fidelity into a common taxonomy which describes simulation fidelity in terms of its specific aspects and elements. This requirement is the basis for research question two.

Definition of Simulation-Based Training and Theoretical Background

Definition of Simulation-Based Training

Miller (1954) referred to simulators as "training devices" and defined them as "a machine whose purpose is to teach job skills which will transfer to operational situations" (p. iii). This definition highlights the first key aspect of simulation-based training; it's an artificial environment used to teach skills which will be used elsewhere. This definition is, like many early views on simulation-based training, narrow because it focuses on the physical equipment used to carry out the training. Miller (1954), however, also noted that of equal importance to the machine was the "program" that it ran. According to Miller (1954) the "program" consisted of the stimuli and context the training device needed to produce in order to induce the same response to stimuli in the learner as would be found in the operational environment. This highlights the second key aspect of simulation-based training; it operates by inducing, in the learner, mental processes as would be found in the operational environment. In this context mental processes refers to both deliberate cognition and the transfer of tacit knowledge (Polanyi, 1966). Tacit knowledge has been included here to account for the transfer of certain fine motor skills such as the amount of force a surgeon needs to apply to an instrument or that a pilot needs to apply to a control. This type of knowledge cannot be transmitted through language, which makes it tacit knowledge. These two key aspects of simulation-based training, (an artificial environment for the acquisition of real-world skills and the induction of real-world mental processes) are echoed in a more modern definition.

Al-Elq's (2010) definition of simulation-based training, "…an artificial representation of a real-world process to achieve educational goals through experiential learning" (p. 1) is consistent with Miller's (1954), but also broader. A process is an abstract concept, which can exist without physical manifestation. Hence, Al-Elq's (2010) view of simulation-based training as a process implies that the core of simulation-based training is not linked to the physical training aids used to carry it out. This opens up a large number of educational and training activities to be considered as simulation-based training.

A key component of Al-Elq's (2010) definition is experiential learning. According to Kolb's (1976) model, two of the key steps to experiential learning are reflection and abstraction. Reflection and abstraction are both cognitive processes. By including experiential learning in their definition, Al-Elq (2010) is implying that part of simulation-based training's purpose is to shape the cognitive process of the learners. This is also consistent with Miller (1954).

In broad terms, both Miller (1954) and Al-Elq (2010) view simulation-based training as a tool for inducing the same mental processes in the learner as would be found in the operational environment. Starting with this as a base premise, it follows that simulation-based training need not be a complete replication of the environment in which the skills will be applied, but rather, it could be a partial replication designed to develop only certain skills, or only parts of certain skills. If the skills to be taught are purely cognitive, then it also follows that a simulation may not necessarily have to include any physical replication of the environment in which the skills will be applied, provided the simulation induces the same mental processes in the learner as the operational environment would. In the most complete sense, (and the sense that will be used in this paper), simulation-based training is any activity that replicates any aspect of an operational environment (either physically or mentally) for the purposes of skill development. This definition is quite broad and includes many potential training interventions ranging from a full motion flight simulator up to and including a simple guided discussion.

Simulation & Learning Theories

Situated Learning

Simulation-based training is a form of situated learning (Lave & Wenger, 1991). According to Lave & Wenger (1991) situated learning takes place in a community of practice where newcomers acquire skills by engaging in legitimate peripheral participation under the guidance of more senior members of the community. In this context a community of practice is a social group which centres around the exercise of certain skills. Medicine, aviation and most other professional fields are examples of communities of practice. Legitimate peripheral participation is the supervised practice of the community's core skill with the implicit objective of passing this skill on to the newcomer; at its core legitimate peripheral participation is an apprenticeship.

In simulation-based training the operational environment is replaced with a simulated one. The other element of situated learning, the legitimate peripheral participation under guidance from senior members of the community, is still there in the form of instructors or facilitators directing the activities of the novices. In the ideal case, in which the simulation is a perfect replication of the operational environment, there would be no difference between situated learning and simulation-based training.

Experiential Learning

Simulation-based training also enables experiential learning. Experiential learning occurs via a cycle of experience, reflection, abstraction and experimentation (Kolb, 1984). This cycle is highly congruent with the definition of simulation-based training developed earlier in this paper.

The simulated environment provides the medium through which the learner experiences the instructional material. In the case of simulation-based training the instructional material consists of the skills targeted for transfer and the environment in which those skills will be used. The degree to which the learner's experience is experiential will depend on the degree to which the simulated environment mimics the operational environment. A simulated environment which offers the learner the full range of cues and the full choice of actions available in the operational environment will be a highly experiential learning environment. As the cues and choice of actions within the simulated environment become circumscribed the learning experience becomes less experiential.

The experiences obtained from the simulated environment will form the basis for the reflection and abstraction required to internalize the material. Note that reflection and abstraction are mental processes and that part of the goal of simulation-based training is to induce the same mental processes in the learner as the operational environment would. In the context of experiential learning this means that the goal is for the simulation to induce the same reflection and abstraction as practice in the operational environment would.

In the experimentation phase of the experiential learning cycle the learner manipulates their environment in order to refine their abstract understanding of the process. Provided the simulation reacts to learner input with sufficient realism, this aspect of experiential learning is also able to be carried out via simulation.

Anchored Instruction

The concept of an instructional storyline found in anchored instruction (The Cognition and Technology Group at Vanderbilt [CTGV], 1990) finds essential application in certain advanced forms of simulation-based training such as Line Oriented Flight Training [LOFT] (Lauber & Foushee, 1981). In these more advanced forms of simulation-based training the learners have already mastered the technical skills of their profession (i.e., the surgeon at this point can suture, the pilot can land an aircraft), but cannot effectively apply these skills in a broader operational context to accomplish an operational goal. Put another way, the learners know how to perform all of the basic skills of their profession, but they don't know how to use those skills to accomplish a broader real-world goal. The purpose of this advanced simulation-based training is to provide a context which teaches the learners how, when and where to apply their basic skills to accomplish an operational goal.

In anchored instruction, learners are provided with a storyline that presents a problem to be solved along with all the data needed to solve that problem and all of the obstacles that must be overcome along the way. The problem, the data, and the obstacles all revolve around skills students have been taught, but have not applied in the real-world (CTGV, 1990). Thus, the instruction is said to be anchored in the storyline. Solving the problem from the story requires the learners to select and apply the appropriate skills, thus helping them develop an understanding of how, when and where those skills are used. This process is virtually identical to the process found in advanced simulation-based training as described above. From a simulation-based training standpoint, the storyline provides the context in which basic skills will be practiced. From an anchored instruction standpoint, the context provides the storyline in which the simulation-based training will be anchored.

Research Questions

This study had three research questions. Research questions one and two were designed to gather and process the information required to build the framework to answer research question three.

Research Question One

Research question one is, "What professional fields use simulation-based training and what skills is it used to teach?" At first glance, the skills taught via simulation-based training appear extremely diverse. For example, the skills an anesthesiologist learns in a simulated operating room bear no immediate resemblance to the skills a nuclear reactor operator learns in a simulated control room. The aim of this research question is to examine and categorize, by schema type, the discreet skills learned in as many simulation environments as practicable. This approach was selected based on the supposition that while there may be significant diversity in the skills taught via simulation-based training there may be some commonalities in the schema types represented by these skills.

The results of the categorization process will be used to build a taxonomy, applicable across professional fields, for the types of skills taught via simulation-based training. This taxonomy will be used as part of the framework for answering research question three.

Research Question Two

Research question two is, "What constitutes fidelity within simulation-based training?" Each professional field describes simulation-based training fidelity differently; there are even substantially different views of fidelity within the same professional field (Jones, 2021). The aim of this research question is to examine the concept of fidelity across professional fields, determine what common elements are present and to categorize these elements.

The results of the categorization process will be used to build a taxonomy, applicable across professional fields, for the elements of fidelity found in simulation-based training. This taxonomy will be used as part of the framework for answering research question three.

Research Question Three

Research question three is, "What is the detailed relationship between skill transfer and the elements of fidelity in simulation-based training?" Previous work (Jones, 2021) indicates that the relationship between the elements of fidelity in simulation-based training and skill transfer to the operational environment is a nuanced one. This research question will apply the taxonomies developed in research questions one & two to make a detailed examination of the relationship between the elements of fidelity, the type of skill being trained and the effectiveness of skill transfer.

Method

Search Strategy

This paper's first objective was to provide the widest practical survey of which professional fields make use of simulation-based training and the skills those professional fields use simulation-based training to teach. With this objective in mind the initial searches were deliberately kept very general. Simple searches for the terms "Simulation Training," "Simulator Training," "Simulator," "Simulation," "Fidelity," "Simulation Fidelity," "Simulator Fidelity," "Simulation Realism" and "Simulator Realism" were carried out using the Omni Search Function of the Ontario Tech University Library, the Embry-Riddle Aeronautical University Scholarly Commons, Google Scholar, PubMed, Medline and the Canadian Forces Staff College Virtual Library online library. Boolean searches of the same sources were carried out using the parameters "Simulator & Fidelity & Transfer," "Simulation & Fidelity & Transfer," "Simulation

& Realism & Transfer" and "Simulation & Fidelity & Transfer." Primary searches began in November of 2021 and concluded in January of 2022. Secondary searches were carried out using selected references from the articles produced by the first search. The secondary searches were carried out between January 2022 and March 2022.

Inclusion Criteria

All screening was carried out manually by the author of this paper. Each research question in this paper had similar, but unique inclusion criteria. Research question one, "What professional fields use simulation-based training and what skills is it used to teach?" had the broadest inclusion criteria. Any paper that described how a professional field used simulation-based training to teach job related skills was included. Peer, or academic review was not a requirement for inclusion. The end result was the inclusion of 96 papers published between 1954 and 2021.

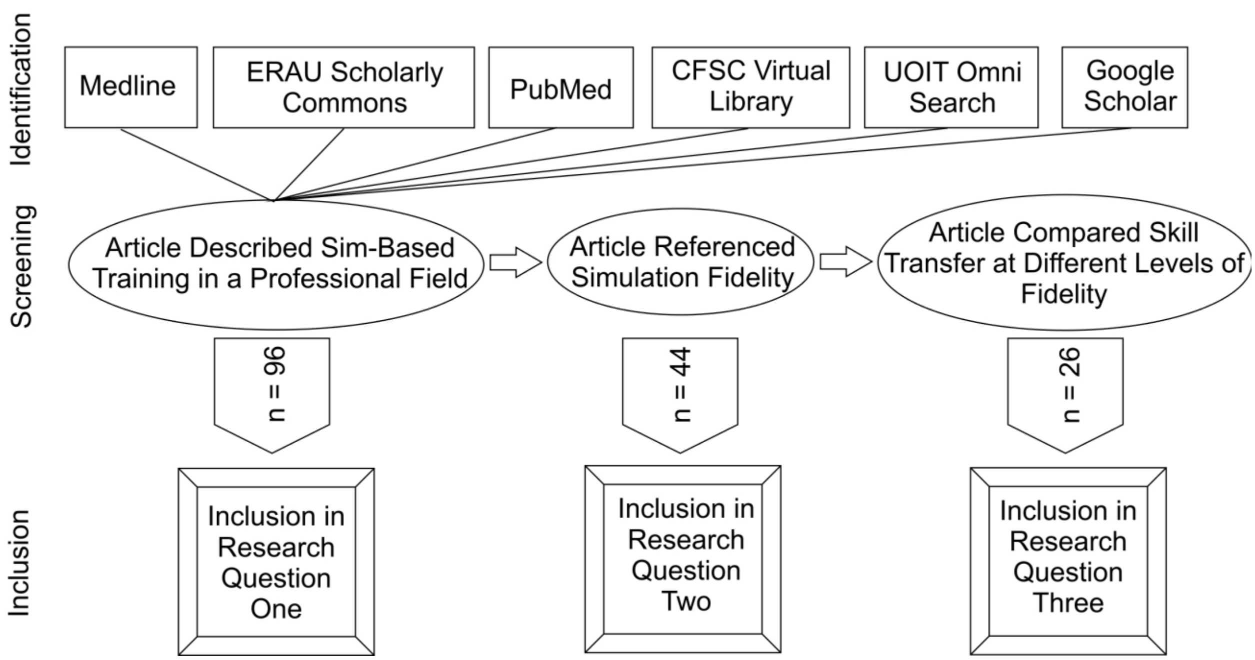
Research question two, "What constitutes fidelity within simulation-based training?" also had very broad inclusion criteria given that its intention was to build a definition of simulation-based training fidelity which would find applicability across a wide range of professional fields. Any paper that contained a description of simulation fidelity in the context of training job skills in simulation-based training was included. The majority of the papers included in this research question were also included in research question one. Peer, or academic review was not a requirement for inclusion. The end result was the inclusion of 44 papers published between 1954 and 2020.

Research question three, "What is the detailed relationship between skill transfer and the elements of fidelity in simulation-based training?", had the strictest inclusion criteria. Only papers that compared transfer effectiveness at two different levels of simulation-based training fidelity were included. Studies which only measured the learners' subjective experiences with various levels of fidelity were excluded. Studies which compared the performance of learners who had received simulation-based training only against the performance of learners who had received no simulation-based training were excluded. The majority of the papers included in this research question were also included in research question one. Peer review, or academic review (such as would be applied to a published doctoral dissertation) was a requirement for inclusion. The end result was the inclusion of 26 papers published between 1976 and 2020.

A flowchart of the search and classification process is presented in Figure 1.

Figure 1

Search and Classification Flow Chart



Skills Taught Via Simulation-Based Training

This section examines which professional fields use simulation-based training to teach job related skills and the nature of the skills so taught. Examining these diverse skills highlights some common traits among them which in turn enables the construction of a taxonomy which is applicable across professional fields. This taxonomy enables a detailed examination of the relationship between simulation-based training fidelity and transfer effectiveness later in this paper.

Each professional field had unique views and descriptions for describing simulation-based training. This lack of uniformity posed a challenged for analysis. This challenge was overcome by employing a two-stage coding process.

Two-stages of coding were required because the initial coding produced descriptions that were still highly specific to individual professional fields. A second stage of coding, which looked for commonalities in the codes produced by the first stage, produced a group of codes that were largely field independent. These second stage codes were used to form a taxonomy to describe the skills taught via simulation-based training. The papers examined, along with the codes assigned to them are listed in Appendix A.

Coding Method

Each of the papers included described the training of unique skills ranging from performing endoscopic surgery (Windrim et al., 2014) to setting up sales displays in a retail store (Leclet & Weidenfeld, 1998). This immense diversity made the data from the searches resemble the data from an open-ended question in a research study. Each paper was, in essence, a response to the question, "Describe what skills you use simulation-based training to teach."

The data's resemblance to that received from an open-ended qualitative research study suggested that it might be appropriate to employ a coding process in order to categorize the skills taught via simulation-based training. To that end a grounded (Bryant & Charmaz, 2016) in vivo (Given, 2008) coding process was used. The initial coding of the data produced broad, first level categories which had narrow applicability, often only being applicable to a single professional field.

The limited applicability of the first level categories made them of little use as a framework for examining simulation-based training across different disciplines. A second round of coding was carried out which looked for common themes among the first level categories. This second iteration of coding produced second level categories which had broader applicability across different profession fields. The first level categories along with a brief description are presented in Table 1 below. .

Table 1

First Level Skill Categories

Category Name	Category Description	Example in Literature
Clinical Motor Skills	This category describes the practice of a discreet motor skill, performed on its own with the objective of building proprioceptive tacit knowledge (Polanyi, 1966) via experiential learning (Kolb, 1976).	Suturing as described by Gonzalez-Navarro et al. (2021) and the manipulation of endoscopic instruments as described by Sabbagh et al.(2012)
Clinical Procedural Skills	This category describes the practice of a sequence of discreet, primarily motor, skills with the objective of building a sequence schema . The sequence may include some cognitive tasks. This category is differentiated from medical treatment management in that the steps in the sequence are prescribed by rote and the learners are not required to use feedback from the simulation to determine what action to perform next. It is used in idealized conditions to teach early-stage novices.	Full surgical procedures as described by Corroenne et al. (2021)
Medical Diagnostic	This category describes the identification of a medical condition based on the static cues the simulation presents.	The rheumatoid arthritis hand models described by Fernandez-Avila et al. (2018)
Medical Treatment Management	This category describes the selection and management of a course of treatment based on the dynamic cues the simulation presents. This differs from the Diagnostic Skills category in that cues the simulation presents emerge over time and may be a result of the learner's inputs into the simulation. This category differs from Clinical Procedural Skills in that the learners are required to decide on a course of action based on the dynamic cues the simulation provides.	The ACLS Training program described by Hoadley et al. (2009)
Team Management	This category describes the ability to work within a team framework, as either a leader or a follower, for the accomplishment of a task.	Beaubien's (2004) description of training health care professionals.

Provider-Client Interaction	This category describes the development of the interpersonal skills, such as empathy and communication, required for people who work with the public (police, waiters, sales staff etc.) to effectively communicate with and manage their clients.	Roleplay, as described by Kase (2016).
Flight Control Manipulation	This category describes the movement of primary flight controls (throttle, stick & rudder) to achieve the desired aircraft performance.	Macchiarella's (2018) description of ab initio flight training in a simulator.
Procedures Training	This category describes the training of a sequence of events such as a drill or a Standard Operating Procedure (SOP). The sequence may involve both motor and cognitive skills. The objective is to enable the learner to perform the sequence by rote.	Reweti's (2017) description of training VFR patterns.
Operational Training	This category describes simulations in which learners must select and implement the correct drill/SOP/checklist based on the cues the simulation provides. The cues may change as the simulation evolves and the simulation may evolve based on learner actions.	Macchiarella's (2018) description of training UAV operators.
Novel Problems	This category describes simulations in which learners are presented with a situation for which there is no standard drill/SOP/checklist and must devise a potential course of action.	The use of microworlds for management training as described by Stouten et al. (2012)
Process Control	This category describes simulations in which learners learn to control an industrial process at a systems level. This is strictly a cognitive exercise; control manipulation does not rely on proprioceptive feedback.	Crichton's (2017) description of an oil drilling rig simulator.
Response to Abnormal Situation	This category describes simulations in which learners learn to recognize and rectify an abnormal situation which is too dangerous to be practiced in an operational environment.	Gaba's (2001) description of a simulation which trains anesthesiologists to recognize and treat rare and life-threatening complications.

Resource Deployment	This category describes simulations in which learners practice deploying resources to achieve goals.	Powell et al (2008) describing a firefighting simulation in which the learner must allocate limited equipment and personnel to discreet tasks within the context of fighting a larger fire.
Situational Assessment	This category describes simulations in which learners, generally military officers, are required to form an overall situational picture by assessing the disposition of the forces deployed against them as well as other factors such as terrain and weather.	Kylesten's (2010) description of how brigade level officers were trained to assess and react to a simulated battle field using a microworld.
Crew Co-ordination	This category describes simulations in which learners form part of a simulated crew, generally in aviation, and must coordinate their efforts to safely accomplish a mission.	Elphick's (1983) seminal description of the Line Oriented Flight Training (LOFT) concept.
Marksmanship	This category describes simulations in which learners train to accurately hit a target using a firearm.	Wei's (2018) description of a small arms trainier.

Summary of First Level Skill Categories

The first level categories tended to be specific to a single professional field. Clinical motor skills, clinical procedural skills, medical diagnosis and medical treatment management, for example, have no application outside of medicine, just as flight control manipulation has no application outside of aviation. While the other categories were not as closely related to a single professional field, none of them found wide applicability across professional fields. This lack of applicability across multiple professional fields meant that either these first level categories did not give a satisfactory answer to the research question or that there was no common link between the skills each professional field used simulation to train. A cursory examination of the first level categories showed some broad themes, namely motor skills, cognitive skills and social skills. These broad themes suggested that a second iteration of coding might yield useful results.

Second Level Skill Categories

The second iteration of coding grouped the first level categories according to the nature of the skills being trained. The most obvious divisions were between motor skills and cognitive skills. Cognitive skills were further broken up into pattern recognition, procedural knowledge and problem solving. A third major division, social skills was added. Social skills are differentiated from cognitive skills, for the purposes of coding, in that cognitive skills were being trained by use of rational thought processes while training social skills tended to rely on intuitive processes such as reading body language. The second iteration of coding produced the second level skills categories which are listed in Table 2.

Table 2

Second Level Skill Categories

Category	Description	Grouped First Level Categories
Motor-Tacit	This category describes motor skills involving tacit knowledge (Polanyi, 1966) (i.e., how much force a learner needs to apply in a surgical procedure). These skills can only be acquired via experiential learning.	Surgical motor skills, marksmanship & flight control manipulation
Cognitive-Procedural	This category describes training the learner to carry out a sequence of discrete tasks which may include both motor tasks and purely cognitive tasks. The sequences taught are linear and do not require the learners to make decisions based on cues from the simulated environment.	Process control, surgical procedural skills & procedures training
Cognitive-Pattern Recognition	This category describes training in which the learner must select a course of action based on the cues presented by the simulation (i.e., dynamic medical symptoms leading to altering a course of treatment for a simulated patient).	Response to abnormal situation, medical diagnosis, operational training, medical treatment management & situational assessment
Cognitive-Problem solving	This category describes training in which the learner is presented with a unique (to them) situation which requires them to synthesize a solution from their broader knowledge.	Resource deployment & novel problems
Social-Transaction	This category describes training in which learners develop skills dealing with other actual humans either as teammates, or as agents of the simulation.	Team management, provider-client interaction and crew coordination

Each of the papers was re-examined using the second level categories. The second level categories mostly, but not exclusively, mapped onto the first level categories that were grouped under them.

The generalized, discipline independent, nature of the second level categories gives a foundational picture of the nature of the skills simulation-based training is used to teach. As such, they provide a clear picture of the generalized, (from a pedagogical point of view), types of skills that simulation is used to train.

Discussion

Table 3 gives a summary of professional fields which produced literature about their use of simulation-based training.

Table 3

Frequency of Appearance of Skill Categories in Literature Arranged by Professional Field

		Frequency of 2nd Level Category Appearance by Professional Field				
Professional Field	No. of Papers	Motor-Tacit	Cognitive-Procedural	Cognitive-Pattern Recognition	Cognitive-Problem Solving	Social-Transaction
Medicine	44	36	37	13	2	6
Aviation	23	19	17	8	3	1
Military	6	1	3	5	3	0
Industrial	5	0	5	3	2	0
Maritime	4	1	3	3	1	2
Management	10	0	2	3	8	2
Emergency Personnel	6	2	2	3	2	1
Driving	2	2	0	0	0	0

It is important to note that there may be professional fields that use simulation-based training which may not show up in this list due to the fact that they have not produced any literature on the subject. Caution is warranted when examining the frequency with which each second level category appears within each professional field in Table 1. The frequency of an individual category directly indicates only how often that category appeared in the literature examined. The frequency of the appearance of a category may or may not be indicative of the prevalence of the skills represented by that category within training for that professional field. The relationship between the frequency of occurrence of a 2nd level skill category and that skill category's importance to a particular professional field is an area which merits further study.

The eight professional fields found are described below.

Professional fields

Aviation. This professional field involves training personnel to operate or direct airborne equipment. It includes pilots, sensor operators, air traffic controllers and unmanned aerial vehicle operators.

Emergency Response. This professional field involves training personnel to respond to emergency situations and includes firefighters and police.

Industrial. This professional field involves training personnel to control industrial processes in real time such as production lines, nuclear power plants and chemical manufacturing plants.

Management. This professional field involves training personnel to oversee the operations of a business. It includes activities such as budgeting, business planning and personnel allocation.

Maritime. This professional field involves training personnel to operate & command ships at sea.

Medicine. This professional field involves training personnel to work in the field of medicine or dentistry. It includes pre-service and in-service training for physicians, nurses, paramedics and dentists.

Military. This professional field involves training personnel to engage in military operations at all levels ranging from the front-line delivery of effects up to and including the strategic allocation of forces.

Driving. This professional field involves the operation of motor vehicles.

Applicability of 2nd Level Skill Categories

The second level skill categories had broad enough applicability to the skills taught by simulation-based training across most of the professional fields. This wide applicability indicates that there is significant commonality among the skills various professional fields teach using simulation-based training. The major exception was driving. The only 2nd level skill category that was found to be applicable to driving was motor-tacit. This is likely due to the small number of papers (2) from that professional field and the narrow focus (simulated motion in driving simulators) of those papers. It is likely that the 2nd level skill categories would be applicable to this field, had the field produced more literature with a broader reach. This assumption will need to be validated in future research.

Taxonomy of Skills Taught via Simulation-Based Training

The broad applicability of these 2nd level skill categories makes them useful as a broad taxonomy to describe the skills being taught in simulation-based training. The ability to parse out and describe the types of skills being taught in a particular instance of simulation-based training may aid in understanding the working dynamics within that learning environment. The taxonomy presented here enables just this sort of parsing, and will be used to analyse the dynamics of several instances of simulation-based training later in this paper.

Section Summary

The data in Table 3 not only indicates which professional fields are conducting academic studies on the use of simulation-based training, it also gives an indication of the types of skills these professional fields are using simulation-based training to teach. As such, the data in Table 3 provide an answer to Research Question One, "What professional fields use simulation-based training and what skills is it used to teach?" The validity of this answer rests on the assumption that data in Table 3 captured a broad enough and accurate enough picture of the professional fields which use simulation-based training. It is possible that other professional fields which use simulation-based training exist, but that this literature search failed to find them due to the fact that these professional fields produced no academic literature on the subject.

The 2nd level skill categories had broad enough applicability to indicate that simulation-based training does share significant commonality (at the pedagogy level) across professional fields. This answers the question of what skills simulation-based training is being used to teach. Further, these skill categories are suitable to form a taxonomy for the classification of skills taught via simulation-based training.

Further work is needed to validate the assumptions upon which these conclusions rest; namely; that the professional fields examined in this paper are representative enough of simulation-based training as a whole to provide a valid picture; that the amount of literature a professional field produces examining the teaching of a particular skill corelates with that skill's importance to the professional field; and that the skill categories would find wider applicability to the professional field of driving once a sufficient volume of literature from that field has been found and analyzed.

The Elements of Fidelity in Simulation-Based Training

This section examines how the different professional fields define fidelity in the context of simulation-based training. These various definitions are used to identify and describe the various elements which constitute overall fidelity. These elements are then developed into a taxonomy for describing fidelity within simulation-based training. This taxonomy enables a detailed examination of the relationship between simulation-based training fidelity and transfer effectiveness later in this paper.

Most professional fields are concerned with the fidelity, or realism, of their simulation-based training. The general, but unproven, assumption is that greater fidelity leads to improved skills transfer. While fidelity is generally considered to be the degree to which a simulation mimics its referent system or process (Miller 1954), this definition lacks the granularity for useful application in determining which aspects of fidelity may be most useful for optimizing skills transfer. Research in each of the professional fields surveyed in this paper examined the concept of fidelity either directly or indirectly. As with the skills taught via simulation-based training, each professional field developed its own terminology and views surrounding what constitutes fidelity.

This section answers research question two, "What constitutes fidelity within simulation-based training?", by examining each professional field's views on the characteristics of fidelity and then grouping these characteristics according to common themes. Each grouping of characteristics constitutes an element of fidelity. For the purposes of this paper, a characteristic of fidelity is a specific trait of a specific simulation, while an element of fidelity is a generalized concept which ties similar characteristics together across different simulations. The simulated resistance tissues apply (known as force-feedback) to the instruments in certain endoscopic surgery simulators, as mentioned by De Witte et al. (2021), is a characteristic of fidelity. The platform motion present in flight simulators, as mentioned by Martin & Waag (1978a) is also a characteristic of fidelity. Both of these characteristics are a manifestation of haptic feedback, (in that they apply forces to the learner's body); hence haptics unite both these characteristics. This makes haptics an example of an element of fidelity. These concepts will be developed in detail later in this section.

Discussion

Early Work

Several authors have broken simulation-based training fidelity into elements. Miller (1954) did seminal work on the relationship between simulation-based training fidelity and skills transfer effectiveness. He broke simulation fidelity into two broad components; engineering fidelity and psychological fidelity. Engineering fidelity generally referred to how closely the physical environment mimicked the operational environment. Engineering fidelity is primarily concerned with the simulator itself and includes such things as the physical appearance and placement of controls, the amount of force required to operate those controls & the visual cues the simulator presents to the learner. Psychological fidelity refers to how closely the responses learned in the simulator match the responses required in the operational environment. From a learning standpoint, psychological fidelity represents how well schema acquired in simulation-based training match schema acquired in the operational environment.

From a functional perspective, under Miller's (1954) model, engineering fidelity exists in order to induce psychological fidelity. Simulation-based training is a form of both situated learning (Lave & Wenger, 1991) and experiential learning (Kolb, 1976). Both of these learning models depend on the learner receiving informational cues through interaction with the environment and then integrating these cues into schema. In order for simulation-based training to be effective it must present cues which are realistic enough (engineering fidelity) to induce the same mental processes as would be found in the operational environment (psychological fidelity). This hierarchy of fidelity elements is a core concept which continues to inform modern work in the area.

All of the research this paper found on fidelity in simulation-based training either directly broke fidelity into elements which were sub-categories of Miller's (1954) engineering & psychological fidelity, or described the elements of fidelity in a manner that was consistent with Miller's (1954) two types of fidelity. What is clear from research conducted post Miller is that Miller's concept of fidelity requires further sub-categorization in order to form a descriptive taxonomy of fidelity in simulation-based training. What follows is an examination of some current thoughts on how to further sub-categorize fidelity in simulation-based training.

Modern Views on Fidelity

Roberts et al. (2020) conducted a survey of simulation-based research and simulation-based training. They also noted a wide disparity of terminology used among and within different professional fields. They concluded that holistic fidelity could be broken into the sub-categories of physical fidelity, functional fidelity & psychological fidelity.

Roberts et al. (2020) viewed physical fidelity as the degree to which the simulation "looks, sounds and feels like" (p. 515) the operational environment. They viewed functional fidelity as how well the simulation mimics "critical aspects" (p. 515) of the operational environment. Psychological fidelity was the extent to which the simulation evoked the same stress, fear, cognitive load and sensory perceptions as the operational environment.

Myers et al. (2018) examined the effect flight simulator fidelity had on learning transfer and came to similar conclusions as Roberts et al. (2020). Both have similar definitions of physical fidelity. Myers et al. (2018) describe functional fidelity as the degree to which the simulator mimics the behavior of the actual aircraft. Myers et al. (2018) use the term cognitive fidelity to describe the items Roberts et al. (2020) listed under psychological fidelity. Roberts et al. (2020) and Myers et al. (2018) developed similar names under which they grouped similar items. Other researchers have come up with different nomenclatures, but use it to describe groupings of concepts similar to those of Roberts et al. (2020) and Myers et al. (2018).

Hontvedt et al. (2019) examined the use of simulation to train ships' bridge crews. They divided fidelity into technical fidelity, (which described how the simulator looked like the operational environment and reacted like the operational environment), psychological fidelity, (which they broke into cognitive & meta-cognitive fidelity) and interactional fidelity which equated to how well the teamwork dynamics and requirements in the simulation mimicked the teamwork dynamics and requirements found in the operational environment. Miller's (1954) original distinction between engineering and psychological fidelity is still clear, and Hontvedt et al.'s concept of the sub-categories of fidelity contains all the same elements as Roberts et al. (2020) and Myers et al. (2018), just grouped differently. All three groups agree that the fidelity of a simulation depends on how closely that simulation mimics the sights, sounds, feel, physical appearance and behaviour of the operational environment. All three groups agree that the degree to which the mental processes the simulation produces in the learners mimics the mental processes the operational environment produces in the learners also determines the fidelity of the simulation.

This pattern is seen again in the work of Yovanoff et al. (2018). Yovanoff et al. studied the use of simulation-based training to teach novice surgeons central venous catheterization. They describe simulation in terms of structural fidelity (the realism of the physical simulation environment) and functional fidelity (the "match between the system and how a user performs a task in it" (p. 1411)). Their version of functional fidelity included using ultrasound images and haptic feedback to guide the placement of a needle.

As seen above, there is wide spread agreement regarding the elements that constitute fidelity in simulation-based training. There is, however, significant divergence regarding grouping and nomenclature for these elements.

A Taxonomy for The Elements of Fidelity

The works cited above established that fidelity is comprised of distinct elements. What is lacking is a common descriptive taxonomy for talking about the application of fidelity to simulation-based training. This sub-section aims to develop such a taxonomy for use later in this paper.

The majority of the works previously cited agree that the effectiveness of simulation-based training depends on how well the simulation induces the same cognitive processes as the operational environment. This even applies to motor skills given that, according to Fitts & Posner's (1967) model, the initial stages of motor skill acquisition are a cognitive process; the learner must actively think about each individual motor movement in the process. This suggests a definition for the first element of fidelity: Cognitive fidelity.

Cognitive Fidelity. Cognitive fidelity is the extent to which the simulation-based training induces cognitive activity similar to that which would occur if the training took place in the operational environment. Learning is primarily a cognitive activity which implies that cognitive fidelity is of paramount importance when it comes to the skills transfer effectiveness of simulation-based training. This position is congruent with Miller's (1954) views on the importance of psychological fidelity.

Cognitive fidelity is unique among the elements of fidelity because it is the only element which the designers of simulation-based training cannot directly manipulate; it is simply not possible to directly program a learner (if it were, teaching would be infinitely easier and infinitely more ethically complex). Instead, the learner's cognitive activity must be influenced by the cues the simulation presents. The designer does have direct control of these cues, and must design them such that they efficiently induce cognitive fidelity. This suggests that building the remainder of this taxonomy so that it groups aspects of fidelity into elements according to the role those aspects play in inducing cognitive fidelity would provide a useful tool for examining the role of fidelity in simulation-based training.

At the simplest level, the learner gains information from the physical cues the simulation provides. The learner uses these physical cues to build a cognitive model of the simulated environment. This suggests that forms of physical fidelity should be included in the taxonomy. There are many different aspects of physical fidelity including visual presentation, sounds, the arrangement of controls, touch and accelerations. The diversity of these aspects dictates against grouping them all together under a single element.

From the standpoint of simulation design, the aspects of physical fidelity can be grouped according to the difficulty involved in producing them. Certain aspects, such as visual presentation, sounds and control arrangements are simple and relatively inexpensive to reproduce (Rehmann et al., 1995). Other aspects, such as force feedback and accelerations are difficult and expensive to reproduce (Rehmann et al., 1995). This suggests that physical fidelity be divided into two sub-elements; physical-static fidelity and physical-haptic fidelity.

Physical-static Fidelity. Physical-static fidelity is the degree to which the static physical aspects of the simulated environment resemble the static physical aspects of the operational environment. Physical static aspects are comprised of all physical aspects of the simulation that do not apply an active force to the learner's body; this lack of active force is why they are referred to as static. Physical-static fidelity includes such things as the placement of controls, the sound of alarms or machinery, and the degree to which the simulation mimics the appearance of the operational environment. This element of fidelity incorporates the static aspects of physical fidelity as described by Roberts et al. (2020) & Myers et al. (2018). It also encompasses the static aspects of technical fidelity as described by Hontvedt et al. (2019) and structural fidelity as described by Yovanoff et al. (2018). The layout of the stations in a maritime simulator's bridge mimicking the layout of the stations on a ship's bridge, as described by Sencila et al. (2020), is a good example of physical-static fidelity.

Physical-static fidelity induces cognitive fidelity by providing an environment in which learners develop transferable motor and recognition schema. A common goal within simulation-based training is to teach learners to recognize relevant cues. This is the formation of associative memory (Sommer, 2012), which is a cognitive process. In order to form recognition schema that will transfer to the operational environment, the cues presented in the simulation must have sufficient physical-static fidelity that they form the same associative memories as would be formed in the operational environment. Hence, the quality of the cognitive fidelity within the learner is, in part, determined by the physical-static fidelity of the simulation.

A similar paradigm exists for the transfer of motor schema, (also called motor memory). Motor memory consists of manipulating physical items in a specific fashion to achieve a specific outcome. (Lee & Schmidt, 2008). The initial stages of motor skill acquisition (the cognitive and associative stages) are cognitive activities (Fitts & Posner, 1967); the learner must consciously think about each motor movement they are making. A simulated environment that physically replicates (has high physical-static fidelity) the layout of the operational environment will force the learner to make motor movements which are identical to those found in the operational environment. Any cognitive activity associated with these movements, such as that described by Fitts & Posner's (1967) model, will be identical to the cognitive activity the operational environment would produce. Again, the quality of the cognitive fidelity within the learner is, in part, determined by the physical-static fidelity of the simulation.

Physical-haptic Fidelity. Physical-haptic fidelity is the degree to which the forces the learner experiences on their body in the simulated environment mimic the forces the learners would feel on their bodies in the operational environment. Examples of this include the forces a pilot feels as their aircraft accelerates and the resistance that various tissues would offer to a surgeon's instruments. This element of fidelity has been separated from physical-static fidelity because of the engineering challenges its implementation poses. The mechanical systems required to produce physical-haptic fidelity can be quite extensive, and expensive, especially in the case of flight simulators. This, combined with the fact that there is a large body of evidence (Martin & Waag 1978a), (Martin & Waag 1978b), (Nicholson et al., 2013) indicating that perfect physical-haptic fidelity may not be required to induce cognitive fidelity means that these aspects of fidelity merit being grouped into their own element for further study.

Physical-haptic fidelity is separated from functional-model fidelity in that the latter refers to the simulation's underlying model's ability to calculate the correct response whether that model is a computer or some other process. On the other hand, physical-haptic fidelity refers to the simulator's ability to implement the correct response. A good example to illustrate this difference is the simulation of an aircraft in inverted flight. The computer model for that simulation could be capable of calculating the forces the pilot would feel in that situation. The actual simulator most likely will not have the ability to invert the pilot.

This element incorporates the dynamic elements of physical fidelity as described by Roberts et al. (2020) & Myers et al. (2018). It also encompasses the dynamic elements of technical fidelity as described by Hontvedt et al. (2019) and structural fidelity as described by Yovanoff et al. (2018). Andersen et al. (2006) provide an excellent example of the application of physical-haptic fidelity with their description of a virtual reality simulation augmented with force feedback equipment.

Physical-haptic fidelity induces cognitive-fidelity via the same process as physical-static fidelity does. For the transfer of motor memory, physical-haptic fidelity provides the force feedback cues required for the cognitive and associative stages of Fitts & Posner's (1967) model. Friedman et al. (2009) provide a good example of this in their description of using simulation-based training to teach doctors to perform a lumbar puncture. In order to successfully perform the procedure, learners must adjust the amount of pressure they apply to the needle as a function of the resistance they feel to the needle's passage. During the learning process the learner reflects on their management of needle force in relation to the procedure's outcome. As per Fitts & Posner's (1967) model, the learner formulates a plan to modify their approach for the next attempt. This is a cognitive process, but it requires haptic cues provided by force feedback in order to function; hence the role of physical-haptic fidelity is to enable cognitive fidelity.

Functional-model Fidelity. Functional-model fidelity is the degree to which the simulation's model's response to inputs mimics the operational environment's response to the same inputs. An input is a learner's or an instructor's actions. Functional-model fidelity is a simulation's ability to calculate what the appropriate cues should be. The other elements of fidelity are concerned with accurately presenting those cues.

Functional-model fidelity is essentially what Myers et al. (2018) described as functional fidelity. The description given by Myers et al. (2018) was limited in that it only considered the physical equipment (the "degree the simulator acts like the real equipment" (p. 5), and did not consider other components of the simulation such as the training scenario. Other components of functional fidelity, such as the training scenario, are considered in functional-situational fidelity which is dealt with later in this paper.

Functional-model fidelity contains the equipment specific elements of functional fidelity as described by Roberts et al. (2020) and the simulation-response elements of technical fidelity as described by Hontvedt et al. (2019). Similarly, the elements of functional fidelity which are concerned with the simulation's response to inputs, as described by Yovanoff et al. (2018), fall under functional-model fidelity. The efforts of Tu et al. (2015) in determining the correct forces to apply to a driver's body during a driving simulation are a good example of functional-model fidelity.

Functional-model fidelity induces cognitive fidelity by enabling experiential learning (Kolb, 1974) and situated learning (Lave & Wenger, 1991). Both of these learning models require the learner to gain authentic experience interacting with the operational environment and then to reflect on that experience. An authentic experience is one that induces the same reflective cognitive processes as would be found if the training took place in the operational environment. For the experience to be authentic, the environment in which it is gained must react in the same manner as the operational environment. The degree to which the simulated environment's response mimics the operational environment's response is functional-model fidelity, therefore functional-model fidelity enables cognitive fidelity by providing authentic experiences to the learner.

Functional-situational Fidelity. Functional-situational fidelity refers to the degree to which the simulation mimics the tasks, and the relationships between the tasks, which would be found in the operational environment. It may be thought of as the context or background script for the simulation. It differs from functional-model fidelity in that functional-model fidelity ensures the realism of how the simulated environment reacts to learner inputs while functional-situational fidelity sets the conditions for what the learner will do in the simulated environment.

Functional-situational fidelity includes the scenario-based aspects of functional-fidelity as described by Yovanoff et al. (2018) well as the scenario-based elements of interactional fidelity as described by Hontvedt et al. (2019).

Functional-situational fidelity can be achieved by applying a form of anchored instruction (CTGV, 1990) to the design of simulation-based training. The scenario for the training, especially in advanced training like that described by Lauber & Foushee (1981), provides the overall goal to be achieved, the information needed to achieve it and any additional constraints. This makes the scenario analogous to a storyline and as such the scenario can be used to anchor the instructional goals of the training. Macchiarella & Mirot's (2018) description of using scenarios to train unmanned aerial vehicle operators is a good example of functional-situational fidelity.

Functional-situational fidelity induces cognitive fidelity by providing an authentic context for situated (Lave & Wenger, 1991) and experiential learning (Kolb, 1974) to take place. Both of these learning models require the learner to gain authentic experience interacting with the operational environment and then to reflect on that experience. Again, an authentic experience is one that induces the same reflective cognitive processes as would be found if the training took place in the operational environment. For the context to be authentic, it must present the same goals, constraints and information as would be found in the operational environment. The degree to which the simulated environment presents the same goals, constraints and information as the operational environment is functional-situational fidelity, therefore functional-situational fidelity enables cognitive fidelity by providing authentic context to the learner.

Functional-social Fidelity. Functional-social fidelity is a special case of functional-model fidelity in which the people, or agents of the simulation acting as people, respond to the simulated situation in a manner similar to that in which they would react in the operational environment. It encompasses the human-centric elements of functional fidelity in the model described by Yovanoff et al. (2018) , the non-cognitive aspects of psychological fidelity as described by Roberts et al. (2020) in their model and the human-centric elements of interactional fidelity as described by Hontvedt et al. (2019) in their model. Functional-social fidelity induces cognitive fidelity via the same mechanism as functional-model fidelity; by providing authentic cues in response to actions. The description of using live actors to play the roles of psychiatric patients during simulation-based violence prevention training, as described by Feinstein & Yager's (2018), is a good example of functional-social fidelity.

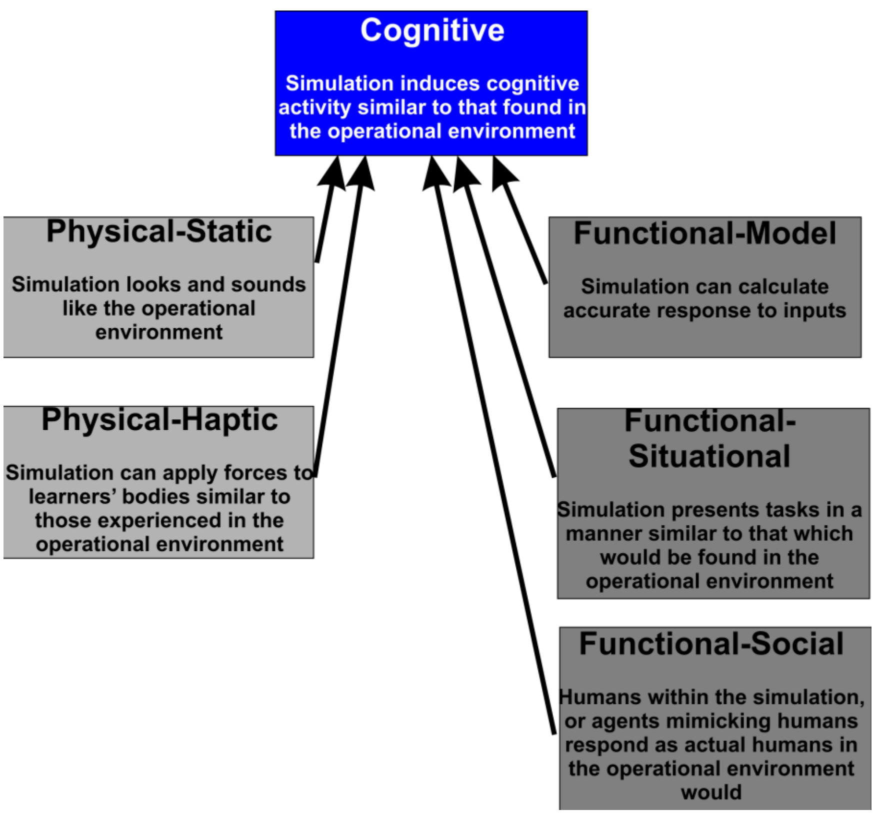
Functional-social fidelity has been separated from functional-model fidelity because of the unique challenges replicating authentic human responses can pose. These unique challenges require solutions which are quite different from the solutions applicable to functional-model fidelity. These unique problems and their solutions mean that functional-social fidelity requires consideration on its own merits.

Section Summary

There is widespread consensus that simulation fidelity can be broken into elements. There is less consensus on exactly how to break overall fidelity into elements, and what to name those elements. This paper offers a proposed taxonomy to describe fidelity within simulation-based training. The elements within this taxonomy are: cognitive-fidelity, physical-static fidelity, physical-haptic fidelity, functional-model fidelity, functional-situational fidelity and functional-social fidelity. Cognitive fidelity refers to how closely the learner's mental processes in the simulated environment mimics the learner's mental processes in the operational environment. All other forms of fidelity exist in order to induce cognitive fidelity. This concept, along with the elements of the proposed taxonomy are presented in Figure 2.

Figure 2

A Proposed Taxonomy for the Elements of Fidelity



The Relationship Between Skills Transfer Effectiveness and Fidelity

This section applies the taxonomies developed earlier in this paper to answer research question three, "What is the detailed relationship between skill transfer and the elements of fidelity in simulation-based training?" Generally, greater fidelity in simulation-based training entails greater costs (Miller, 1954). An understanding of the relationship between the elements of fidelity and skills transfer effectiveness will enable designers of simulation-based training to devote appropriate resources to the appropriate elements of fidelity in order to optimize skill transfer effectiveness.

Detailed review of the studies found in the literature search revealed subtle and useful aspects of this relationship. The first finding was that increased fidelity in cues which were not used in the development of the targeted skills did not result in greater skills transfer. Conversely, increased fidelity in cues which were used in the development of the targeted skills often resulted in increased skills transfer. Put another way; the elements of fidelity in which the simulation-based training was high fidelity had to match the type of skills which the simulation-based training was designed to teach.

The literature showed that even if the elements of increased fidelity did match the type of skills to be taught, the increased fidelity did not always result in increased skills transfer (Lintern & Garrison, 1992). What the literature indicated was that there may be a critical threshold level of fidelity required for improved skills transfer. Levels of fidelity below this threshold result in ineffective skills transfer, while levels of fidelity above this threshold result in effective skills transfer. There were further indications that increases in fidelity beyond this minimum threshold did not result in improved skills transfer effectiveness. The volume of literature that showed this phenomenon was quite small, hence the results are only indicative and far from conclusive. This relationship is worthy of further study with the goal of verifying this threshold's existence, and quantifying this threshold should it be found to exist.

Studies Which Found No Advantage to High-Fidelity

None of the studies examined broke their simulation fidelity into elements; they simply referred to the simulation as being either high-fidelity or low-fidelity. The classification of elements of fidelity was done by the author of this paper by reading the studies' descriptions of their different simulators and applying the taxonomy for the elements of fidelity developed earlier. None of the studies had simulations that differed in all elements of fidelity. These studies compared simulations in which only one aspect of the simulation's fidelity changed between the control and experimental groups.

Studies that found no advantage to high-fidelity simulation fell into one of two groups once they were analyzed using the taxonomies developed earlier. The first group were studies in which the fidelity of the simulator changed between the experimental and control groups, but alternative means were used to provide learners in both groups with the same information, thus making both overall simulations of equivalent cognitive fidelity. The second group were studies in which the high-fidelity cues in the high-fidelity simulation were not related to the skills being targeted or measured.

Overall Simulation Fidelity Depends on More than Simulator Fidelity

Finan et al. (2012) provide the best example of studies in which simulator fidelity changed between the control group and the experimental groups but alternative methods were used to provide the learners with the same information. They studied the difference in skills transfer effectiveness between low-fidelity simulation and high-fidelity simulation when teaching neo-natal resuscitation skills. Resuscitation involves recognizing the symptoms a casualty presents (heart rhythm, respiration rate, skin tone etc.), selecting the correct course of action and then implementing that course of action. Selecting a course of action based on cues is a cognitive-pattern recognition task and implementing a course of action is a cognitive-procedural task.

In the study by Finan et al. (2012) the low-fidelity simulation was a static mannequin which presented no data on its own. The high-fidelity simulation was a computerized mannequin capable of mimicking the casualty's physiological responses (skin colour, heart/breath sounds etc.). The high-fidelity simulation also had a simulated vital signs monitor (heart rhythm, respiration, etc.). The mannequin used in the high-fidelity simulation had greater physical-static fidelity (skin colour, heart & breath sounds etc.) as well as greater functional-model fidelity (providing a realistic response to the learners' actions by altering the heart rhythm, skin colour or heart & breath sounds). The high-fidelity simulator (in this case the mannequin) clearly provides cues of a higher-fidelity which are relevant to the task. This evokes the question, why didn't the high-fidelity simulation provide superior skills transfer?

In the study by Finan et al. (2012), a facilitator was present in the low-fidelity simulation to provide learners with information regarding the casualty's vital signs. This facilitator could tell the learners what the casualty's heart rhythm was, what sort of heart & breath sounds were present, etc. The presence of the facilitator in this simulation ensured that, from a cognitive standpoint, the learners had access to all of the same cues that were available in the high-fidelity simulation. While the low-fidelity mannequin, (the simulator) itself did not provide the learners with a full set of realistic symptoms, the overall simulation, (via the facilitator) did. From a standpoint of cognitive-fidelity, both overall simulations provided the learners with the same cues, and were hence of equal fidelity. This explains their equivalence in effectiveness. This situation was repeated when Hoadley's (2009) study found that high-fidelity simulation did not provide greater effectiveness than low-fidelity simulation for teaching Advanced Cardiac Life Support (ACLS). The high-fidelity simulation was once again a mannequin which provided all vital signs to the learners while the low-fidelity simulation consisted of a static mannequin and a facilitator to tell the learners what vital signs the mannequin was displaying. Again, the tasks being assessed were cognitive-pattern recognition and cognitive-procedural. Both simulations provided the learners with all of the cues required and were hence of equal cognitive fidelity which explains the lack of difference in the skills transfer effectiveness. Curran et al. (2014) conducted a study similar to Hoadley's (2009). Curran et al. (2014) studied the effect of fidelity on the transfer of neo-natal resuscitation skills using high-fidelity mannequins (which provided all of the physiological data learners needed to make a diagnosis/choose a course of action) and low-fidelity mannequins which provided limited physiological cues but were supplemented by a facilitator who provided the learners with the required cues. Again, the overall simulations were of equivalent functional-model fidelity and again the results showed that there was no difference between the two simulations for effectiveness of skills transfer.

Increased Fidelity Must Be Related to Cues Relevant to the Task Being Trained

Morgan & Hegarty's (2006) study comparing high-fidelity simulation to low-fidelity simulation for teaching resuscitation knowledge provides the best example of high-fidelity simulation elements not being relevant to the skills being targeted for transfer. The workshop consisted of both didactic and simulation training. In this study the low-fidelity simulation consisted of a standard CPR mannequin (low physical-static fidelity) with a facilitator present to provide cues as to the simulated patient's condition. The high-fidelity simulator consisted of a full body mannequin (high physical-static fidelity) which mimicked the physiological cues given by a real patient. The study used a multiple-choice test to measure the acquisition of declarative knowledge after the simulation training sessions. The studied found that both levels of simulation fidelity resulted in the same level of acquisition of declarative knowledge.

The multiple-choice test measured simple recall of knowledge (Bloom & Krathwohl, 1956). This knowledge was likely gained during the didactic portion of the workshop and most likely quite disconnected from the physical-static elements of the simulation. In essence, the high-fidelity elements of this simulation were unrelated to the metrics used to judge the effectiveness of skill transfer. In fact, it could be argued that the metrics used were not related to the simulation at all. The fact that the element of increased fidelity (physical-static) was unrelated to the skills targeted for transfer explains why increased fidelity had no effect on skills transfer effectiveness.

Morgan & Hegarty (2006) were not the only ones to study the relationship between physical fidelity and the effectiveness of cognitive skill transfer in simulation-based training. Howard (2013) found no differences in the transfer of critical thinking skills in nursing students trained using a high-fidelity mannequin vs. nursing students trained using a computer-based patient simulator. The computer-based simulator presented learners with a scenario by describing a patient's symptoms using both text and graphics. The learner then selected an action and the software would calculate and present the patient's response within the scenario via updated vital signs and a new set of symptoms; this cycle repeated until a resolution of the scenario was reached. The high-fidelity mannequin looked like a human being and provided all of the physiological cues relevant to the scenarios being taught. Learners interacted with the mannequin by performing actual medical procedures on it, and the mannequin's software altered the mannequins' vital signs in response to learner actions within the scenario.

The high-fidelity simulation had higher physical-static & physical-haptic fidelity. Both simulations had equivalent cognitive-model fidelity in that both calculated the same response to learner and scenario inputs. Howard (2013) was measuring critical thinking skills in a nursing context; this translates to a cognitive-problem solving task. A cognitive-problem solving task, especially one like medical treatment which is dynamic in nature and evolves over the course of the scenario, relies very heavily on the simulation responding realistically to the inputs of the learner and the scenario; i.e., it relies heavily on functional-model fidelity. Again, the high-fidelity simulation's high physical-static and physical-haptic fidelity did not provide cues relevant to the transfer of the skills being evaluated, and hence provided no advantage.

While Morgan & Hegarty (2006) provide the most extreme example of trying to improve skills transfer by increasing the fidelity in an element not relevant to the skills targeted for transfer, there are numerous other, less extreme examples available in the literature reviewed. Katayama et al. (2019) studied the transfer of needle cricothyroidotomy skills using simulators of different fidelity levels and found there was no advantage to high-fidelity simulation. A cricothyroidotomy involves piercing a casualty's throat with a needle in order to deliver oxygen to the lungs in an emergency situation. The success of this procedure depends on placing the needle through the correct gap, (the cricothyroid membrane), in the underlying structures of the throat (Cape Town Emergency Medicine, 2013). This gap is found by palpitating the throat's underlying anatomy through the skin. Palpitation is a motor-tacit skill, as is guiding the needle for correct placement during insertion.

The low-fidelity simulators for this study were plastic models of the gross anatomy of the throat's internal structures covered by a thin sheet of plastic to simulate skin. The anatomy these simulators mimicked was limited to only those structures required to identify the correct insertion point for the needle and to mimic the resistance of the various tissues to the needle's passage. The plastic model used to simulate the throat's underlying anatomical structure did not mimic the visual appearance of the throat's underlying anatomical structure to a high degree. The plastic sheet used to simulate skin did not mimic the visual appearance of skin to a high degree. The high-fidelity simulator consisted of a detailed 3D printed model of the throat's underlying anatomy covered by artificial skin. Both the underlying anatomy and the overall simulator mimicked the visual appearance of a human throat to a high degree. Hence, the high-fidelity simulator was of higher physical-static fidelity.

As was explained earlier, the execution of this procedure relies primarily on motor-tacit skills and hence requires accurate haptic feedback for proper skill transfer making physical-haptic fidelity the predominate factor for determining the simulation's effectiveness. While the high-fidelity simulator looked more like a real throat, both on casual inspection and during dissection, than the low-fidelity simulator did, it did not feel like a real throat any more than the low-fidelity simulation did; i.e., the two simulators were of equal physical-haptic fidelity. Hence, for the purposes of the skills being trained, both the simulators were of equal fidelity which would explain their observed equivalency of effectiveness.

The studies examined so far have all used high physical-static fidelity in an attempt to improve the transfer of skills not related to physical-static fidelity. While this is a common theme in the literature reviewed, there are cases where simulations have been high-fidelity in elements other than physical-static fidelity, and those high-fidelity elements have not been relevant to the skills targeted for transfer. Tuzer et al. (2020) provides a good example.

Tuzer et al. (2020) compared the use of high-fidelity and medium-fidelity simulation for teaching CPR and found that both levels of fidelity were equally effective for skills transfer. The high-fidelity simulation in this case consisted of CPR training carried out using a standard CPR mannequin in a scenario-based learning environment. Learners were placed into a simulated emergency situation and had to choose and implement the correct CPR procedure based on the cues presented in the scenario. This simulation is high in functional-situational fidelity and would be well suited for training cognitive-pattern recognition skills or cognitive-problem solving skills. The medium-fidelity simulation used a standard CPR mannequin and the learners practiced CPR as a simple psycho-motor skill; i.e. the learners were told which CPR skill needed to be practiced and had no need to make any decisions. This simulation was of lower functional-situational fidelity than the high-fidelity simulation but equivalent in all other elements of fidelity. The study evaluated training effectiveness by measuring how well the learners physically performed CPR and measured such things has hand placement, rate of compressions and the correct order of steps. Decision making and teamwork skills were not measured, and hence the evaluation of training effectiveness was based strictly on a measurement of motor-tacit skills and cognitive-procedural skills which rely on cues provided by physical-haptic and physical-static fidelity. Given that both simulations were of equivalent fidelity as far as the skills measured were concerned, it is unsurprising that the study found high-fidelity simulation to be of equal effectiveness as medium fidelity simulation. Had the study measured the learners' ability to make decisions based on situational cues, (i.e., cognitive-problem solving skills), the results may have been different. Again, the skills targeted for transfer in this simulation were unrelated to the high-fidelity elements of the simulation which explains why high-fidelity simulation did not show increased effectiveness. This theme continues in Adams et al. (2015).

Adams et al. (2015) studied the difference in transfer effectiveness between low-fidelity and high-fidelity simulation for teaching ACLS to novice learners. ACLS involves selecting the correct course of action (medication administration, chest compressions, defibrillation, etc.) based on the patient's vital signs (primarily heart rhythm, but also considering respiration rate and other physiological indicators) (Oxford Medical Education, 2017). The low-fidelity simulation consisted of computer software which mimicked the various cardiac conditions, and the patient's response to the learner's intervention. The software displayed results on a simulated cardiac monitor. The low-fidelity simulation consisted of only the monitor, and no mannequin. The high-fidelity simulation consisted of software similar to that of the low-fidelity simulation which displayed calculated vital signs on a monitor similar to that from the low-fidelity simulation. The only major difference between the low-fidelity simulation and the high-fidelity simulation was the addition of a mannequin to the high-fidelity simulation. The mannequin enabled learners to physically carry out the actions involved in ACLS (medication injection, defibrillation, chest compressions etc.) in the high-fidelity simulation whereas in the low-fidelity simulation the learners merely verbally identified the action to be carried out without physically doing the action. Hence the high-fidelity simulation had higher physical-static and physical-haptic fidelity. However, both simulators provided the same information regarding the patient's vital signs and their reaction to learner actions. Hence, both simulations were of equivalent functional-model fidelity.

The critical skill taught in ACLS, and the critical skill evaluated in this study, was the selection of the correct course of action based on the patient's vital signs and the reaction of those vital signs to learner intervention (Oxford Medical Education, 2017). This is a cognitive-pattern recognition skill and is heavily reliant on functional-model cues, and to a lesser extent physical-static cues. In these two respects, the two simulations in this study were equivalent, which explains the lack of improved transfer effectiveness for the high-fidelity simulation. Again, we see that increased fidelity in non-relevant cues provides no benefit for the learner.

Denadai et al. (2014) found that increased physical-static fidelity had no effect on transfer effectiveness when teaching a cognitive-procedural skill. Denadai et al. (2014) studied the effect of low-fidelity simulation vs high-fidelity simulation when teaching surgical excision skills. The low-fidelity simulation in this case was either an orange peel or a piece of plastic film while the high-fidelity simulation was a piece of full thickness chicken skin. The chicken skin looked more like human skin; hence the high-fidelity simulator was of greater physical-static fidelity. The high-fidelity simulator may, or may not have, been of greater physical-haptic fidelity; the study offers no data on this point. The instrument used to measure skill transfer was a checklist that focused on whether the learners had carried out the correct steps in the correct order. Hence, the skills measured were of a cognitive-procedural nature. Denadai et al. (2014) found that both simulators were equally effective. This is most likely due to the fact that both simulators were equivalent from a functional-model fidelity stand point; both simulators reacted in the same manner to the application of the scalpel. The simulators had equal effectiveness because they had equal fidelity in terms of the cues used to teach the skills measured. Had the study measured the motor-tacit skills required to perform an excision, the end results on skills transfer may have been different.

Friedman et al. (2009) provide another example of how increased physical-static fidelity has no effect on the transfer of motor-tacit skills. Friedman et al. (2009) studied the effects of increased physical-static fidelity on training anesthesiologists in needle placement for an epidural procedure. The high-fidelity simulation was a life size picture of the back of a human being with appropriate hardware attached to simulate the resistance of various tissues to the passage of the needle. The high-fidelity simulator was also equipped with a virtual-reality display which showed needle progress. The low-fidelity simulator was a banana. The high-fidelity simulator was of greater physical-static fidelity, but according to the authors of the study, it was of roughly equivalent physical-haptic fidelity to the banana in terms of representing the resistance of various tissues to the needle's passage. According to the authors of the study, the placement of the epidural needle requires the learner to identify the correct amount of pressure to apply as a function of the needle's progress. This makes inserting the needle a motor-tacit skill which in turn means that it will rely on physical-haptic cues. The fact that both simulators were of equal physical-haptic fidelity explains why they were of equal effectiveness for the transfer of this skill. The high-fidelity cues provided by the high-fidelity simulator were not relevant to the skill being taught.

In a study similar to that of Friedman et al. (2009), Gonzalez-Cota et al. (2013) studied the effects of high-fidelity simulation vs low-fidelity simulation for training fluoroscopic guided epidural needle placement. They found that there was no increased transfer effectiveness for the high-fidelity simulation. Again, the difference between the high-fidelity simulation and the low-fidelity simulation was that the high-fidelity simulator was a mannequin of a human torso with detailed internal anatomy which was visible under fluoroscopic. The low fidelity simulation was a metallicized model of a human spine sandwiched between various layers of foam to emulate the resistance of various tissues to needle passage. The high-fidelity simulator looked more like a human, and hence was of greater physical-static fidelity.

During a fluoroscopically guided epidural the learner uses a real time x-ray monitor to guide the needle into the correct position. The learner uses the cues provided from the x-ray machine (the fluoroscope) to do this (The Spine and Pain Institute of New York, 2016). Hence, the effectiveness of the simulation is dependant on how well the simulator (the mannequin and the foam-wrapped spine model in this case) mimic the x-ray pictures from a real human body. In other words, the effectiveness of the simulation relates to the functional-model fidelity of the simulator. In this case, both simulators gave roughly equivalent fluoroscopic pictures, and were of equal functional-model fidelity. Again, the high-fidelity simulation did not show any advantage in transfer effectiveness because its high-fidelity elements, (physical-static), did not provide cues relevant to the skills targeted for transfer.

Curran et al. (2014) found that high-fidelity simulation had no advantage over low-fidelity simulation for the transfer of teamwork skills in neo-natal resuscitation training. Teamwork skills consist of interacting with other individuals during a task; this makes them social-transaction skills.

Social-transaction skills, especially teamwork skills, often involve either the completion or assignment of tasks within the framework of a social group. The individual tasks themselves are usually not the end goal in the process, but rather serve as steps towards attaining a desired end state. For example, in Curran et al.'s (2014) study the desired end state was the resuscitation of the casualty; some of the required processes for this might include the preparation and administration of medication, the application of chest compressions and the intubation of the casualty. Successful attainment of the desired end state requires all of these tasks to be done in the correct fashion and at the correct time and place. In other words, the successful attainment of the desired end state is predicated on the maintenance of the correct relationship between each of these individual tasks within the team framework. It stands to reason that the transfer of these tasks via simulation-based training would require the simulation to accurately mimic the relationship between these individual tasks. Accurate representation of the tasks within a situation and the relationship between those tasks falls under the element of functional-situational fidelity. Social-transaction skills also involve working with the reactions of actual people, hence they also involve functional-social fidelity. Hence, the tasks that Curran et al. (2014) were trying to train were dependent on functional-situational and functional-social fidelity.

In the study by Curran et al. (2014) the high-fidelity simulation consisted of high-fidelity mannequins (which provided all of the physiological data learners needed to make a diagnosis/choose a course of action) and the low-fidelity simulation consisted of mannequins which provided limited physiological cues but were supplemented by data from a facilitator who provided the learners with the required cues. The scenario in both simulations consisted of the same tasks and maintained the same relationship between those tasks. This makes both simulations of equal functional-situational fidelity. Again, the high-fidelity elements, (physical-static), did not provide cues which were relevant to the skills, (social-transaction), targeted for transfer. As a result, the high-fidelity simulation had no advantage over the low-fidelity simulation for transfer effectiveness. The disconnect between physical-static fidelity and social-transaction skills is further highlighted in the work of Gu et al. (2017).

Gu et al. (2017) also showed that increased physical-static fidelity had no effect on the transfer of social-transaction skills. Gu et al. (2017) studied the transfer of decision-making skills, situational awareness, communications skills and leadership skills in both high-fidelity and low-fidelity simulations. Decision-making involves selecting a course of action based on the cues presented. This makes it a cognitive-pattern recognition or cognitive-problem solving skill. Situational awareness is the ability to form a mental picture of the current situation and to predict how it will evolve (Endsley, 1988), which also makes it a cognitive-pattern recognition skill.

Communications and leadership skills are social-transaction skills. Hence, Gu et al. (2017) were targeting the transfer of cognitive pattern recognition skills and social-transaction skills.

Cognitive-pattern recognition skills rely on dynamic cues presented by the simulation in response to the learner's actions within the simulation. These types of cues fall under functional-model fidelity and potentially under physical-haptic fidelity. Social-transaction skills rely on cues that are provided by functional-social fidelity.

In Gu et al.'s study the high-fidelity simulation consisted of a full body mannequin connected to a vital signs monitor which provided a full suite of physiological data to the learners. The low-fidelity simulator consisted of a simple upper-torso mannequin which was also connected to a vital signs monitor which provided the learners with a full suite of physiological data. The high-fidelity simulation was of higher physical-static fidelity, but of equal fidelity in all other elements. The fact that the skills targeted for transfer relied on functional-model and functional-social fidelity, and that both simulations were of equal functional-model and functional-social fidelity explains why the high physical-static fidelity simulation had no advantage. Again, the high-fidelity elements of the simulation were unrelated to the skills targeted for transfer.

Lintern et al. (1989) found similar results to the studies cited above when they studied the relationship between physical-static fidelity and transfer of tasks of a cognitive-procedural or motor-tacit nature in aviation. Lintern et al. (1989) studied the relationship between the fidelity of the visual display (physical-static fidelity) and transfer effectiveness when training U.S. Navy pilots in aerial weapon delivery. Aerial weapon delivery involves a series of steps, both motor and cognitive, which must proceed in synchronization with cues from the outside environment. This makes aerial weapons delivery a cognitive-procedural skill. Some of the motor skill steps involved in aerial weapons delivery involve the manipulation of flight controls thus making aerial weapons delivery a motor-tacit skill as well.

Cognitive-procedural skills rely on functional-model fidelity in that the development of these skills depend on the simulation providing the correct cues based on the learners' inputs. The motor-tacit skills in this simulation rely on physical-haptic fidelity in that they require the simulation to provide correct control pressure feedback and forces on the pilots' body. Both the high-fidelity simulation and the low-fidelity simulation in this study used the same computer model to generate the simulation cues and provided the same control pressure feedback and forces on the pilots. The net result was that the high-fidelity elements (physical-static) of the simulation did not provide cues which were relevant to the skills targeted (cognitive-procedural & motor tacit) for transfer and the high-fidelity simulation had no advantage over the low-fidelity simulation in terms of transfer effectiveness.

Reweti et al. (2017) found similar results to Lintern et al. (1989). Reweti et al. (2017) found that there was no difference in skills transfer effectiveness for pilots learning landing patterns in a high-fidelity flight simulator vs pilots learning the same procedure in a low fidelity personal computer-based flight simulator. A visual-landing pattern requires a pilot to manipulate flight controls to ensure the aircraft follows a specific path over the ground while maintaining altitudes and airspeeds which are dependant on which stage of the procedure the aircraft is in. (Transport Canada, 2004). A visual-landing pattern is a combination of cognitive-procedural and motor-tacit skills. Pilots learn to do visual-landing patterns by using visual cues from the outside view to monitor the aircraft's attitude and path over the ground as well as cues from the instruments to gauge certain aspects of the aircraft's performance such as airspeed and altitude. These cues change in response to the learner's input as well as in response to the progression of the procedure. Based on the cues used, this procedure relies on functional-model fidelity and on certain aspects (outside view and instrument presentation) of physical-static fidelity.

In Reweti et al. (2017), the high-fidelity simulator was a mock-up of an actual aircraft cockpit with an outside visual display. The low-fidelity simulator consisted of several large computer monitors (sufficient to give a field of view roughly equivalent to the high-fidelity simulator) and a full set of mock aircraft controls all mounted on a desk. The low-fidelity simulator did not look like the inside of an aircraft cockpit, but it provided all of the cues and controls required for a pilot to control an aircraft. More importantly, it provided all of the same operational cues (the outside visual display and the cockpit instrument displays) as the high-fidelity simulator. Both simulators used essentially the same computer model to determine aircraft responses, hence both simulators were of equivalent functional-model fidelity.

The high-fidelity elements of the high-fidelity simulator, (its resemblance to the inside of an aircraft cockpit), did not provide cues relevant to the skills targeted for transfer, (manoeuvring of the aircraft with reference to the external visual cues and the instrument indications), hence the high-fidelity simulation had no advantage in terms of transfer effectiveness.

Studies Which Found Increased Fidelity Improved Skills Transfer

Nicolaides et al. (2020) studied the transfer of team performance skills in high and low fidelity simulation-based training. They found that the high-fidelity simulation led to better transfer of leadership, teamwork and task management skills. Leadership and teamwork skills are social-transaction skills while task management is a cognitive-problem solving skill. The low-fidelity simulation in this study consisted of managing the care of a single patient represented by a mannequin. The high-fidelity simulation consisted of managing multiple trauma cases represented by real humans wearing realistic costumes to simulate injuries.

The simultaneous multiple trauma cases in the high-fidelity simulation presented the learners with multiple tasks and forced them to manage the execution of those tasks. This represents greater functional-situational fidelity which provides the types of cues, (the need to allocate resources), that constitute a novel problem for the learners. These are exactly the type of cues and fidelity needed to develop the cognitive-problem solving skills which leadership and teamwork represent. The higher work load in the high-fidelity simulation would have also resulted in a higher level of stress within the team environment. This, combined with the fact that the high-fidelity simulation used standardized patients, increased the functional-social fidelity which supported the development of the social-transaction skills of teamwork and leadership.

Gundry (1976) as cited by Hall (1989) found that greater fidelity, in the form of disturbance motion, led to greater skill transfer, in the form of more accurate flying, when teaching pilots to fly a precision approach under instrument conditions. Flying under instrument conditions deprives the pilot of the normal visual cues, (the horizon), used for orientation. The pilot must instead rely on a deliberate and systematic scan of the aircraft instruments while learning to selectively ignore certain proprioceptive cues (Transport Canada, 1997). Flying a precision approach under these conditions requires making numerous and rapid small corrections and is a cognitive-procedural skill and a motor-tacit skill.

Disturbance motion is short duration small amplitude accelerations applied to the pilot; it is meant to simulate turbulence. Disturbance motion falls under physical-haptic fidelity. In the operational environment disturbance motion provides an immediate cue that the aircraft’s flight attitude may have changed and triggers the pilot to direct their attention to the correct instrument. Failure to rapidly attend to this cue will result in degraded aircraft control. The immediate direction of the eyes to the appropriate instrument upon the detection of disturbance motion is a motor-schema, verging on a trained reflex. Thus, the reaction to disturbance motion is a motor-tacit skill.

The increased physical-haptic fidelity represented by disturbance motion provided cues relevant to the motor-tacit skill being trained, (the direction of the eyes to the correct instrument and the suppression of a reaction to the pure vestibular sensations). In other words, the high-fidelity elements provided cues relevant to the skills targeted for transfer. The net result is that the simulation had greater cognitive-fidelity and greater skills transfer effectiveness.

Rodgers et al. (2009) provide a good example of how relevant cues can improve skill transfer effectiveness. Rodgers et al. (2009) studied the effectiveness of high-fidelity simulation vs low-fidelity simulation for skills transfer in the ACLS course. As with previous studies the high-fidelity simulation was a highly automated mannequin which provided simulated vital signs and symptoms in accordance with the scenario and the learner's actions. The low-fidelity simulation was a simple CPR mannequin with an instructor present to provide information regarding the patient in response to learner queries.

Rodgers et al. (2009) broke ACLS into a number of sub-skills and analyzed the transfer effectiveness for each of those sub-skills. The majority of these sub-skills were either motor-tacit tasks or cognitive-procedural tasks. Rodgers et al. (2009) found that the high-fidelity simulation had no advantage over the low-fidelity simulation for the motor-tacit and cognitive-procedural tasks. The near equivalence of the two simulations in terms of cognitive-model fidelity, physical-static and physical-haptic fidelity account for this finding. Rodgers et al. (2009) also found that the high-fidelity simulation showed superior transfer effectiveness for certain situational management tasks. Specifically, they found that the high-fidelity simulation had more effective transfer in the tasks of; “Team leader assured that high-quality CPR was in progress,” “Team leader recognized initial ECG rhythm,” “Team leader followed appropriate ACLS algorithm,” and “Team Leader Recognized ECG Changes.”

These tasks require the team leader, (the learner in the case of this study), to effectively direct their attention to the appropriate cue at the appropriate time. Poor performance on these items is indicative of ineffective allocation of attentional resources. Assuring that high quality CPR is in progress requires the team leader to periodically direct their attention to the performance of the team member performing CPR. The recognition of an ECG rhythm and following the appropriate ACLS algorithm are cognitive processes, which require focused attention at appropriate times. The recognition of ECG changes requires the team leader to monitor the ECG at appropriate times and act accordingly. Managing all of these tasks requires the learner to constantly shift their attention around the simulation environment.

Knowing where to direct one’s attention at what times during a task, (such as managing a cardiac crisis), in order to monitor relevant cues is a crucial skill which requires practice in the operational context (Transport Canada, 1997). This skill is essentially allocating attention to the individual tasks involved in achieving the overall aim. This attentional allocation is a cognitive-problem solving task and its development requires a learning environment that adequately replicates the tasks, and the relationships between them, found in the operational environment. Development of this skill requires functional-situational fidelity.

The main difference between the high-fidelity simulation and the low-fidelity simulation in Rodgers et al. (2009) was the process by which the learner gathered information about the patient. In the low-fidelity simulation the learner was trained to ask the instructor for the required information. In the high-fidelity simulation the learner was trained to gather the required information by seeking it from the cues in the simulation environment. From this view point the high-fidelity simulation had higher functional-situational fidelity in that it required the learner to physically direct their attention to the appropriate cue, (the movement of the chest for breathing, skin tone for profusion etc.), as compared to the low-fidelity simulation which merely required the learner to ask the instructor for the required information. Hence, the high-fidelity simulation was more effective for the transfer of this attentional allocation skill.

The high-fidelity simulation produced better results in situational management tasks because it provided cues which led the students to develop effective attention allocation skills. Again, higher-fidelity in the cues used to develop a skill led to more effective transfer of that skill.

Sabbagh et al. (2012) found that increased physical-static fidelity led to improved transfer effectiveness for cognitive-procedural skills. They studied the effectiveness of low-fidelity, non-task specific simulation vs high-fidelity simulation for the transfer of laparoscopic surgical skills. In their study, one group of learners trained by practicing laparoscopic suturing on a foam pad, while the other group trained by practicing a laparoscopic anastomosis on a latex model of the human bladder and urethra. The transfer effectiveness was measured by having both groups perform a bladder anastomosis on an anesthetized pig. An anastomosis requires the surgeon to place a series of sutures in the correct positions, in the correct order while manipulating the surrounding tissues in order to maintain access to the surgical field (SpringerVideos, 2010). This makes it a cognitive-procedural task.

The high-fidelity simulation had greater physical-static fidelity in that the latex structures closely mimicked the shape, size and relative positions of the actual structures whereas the foam pad was a simple rectangle of foam which bore little resemblance to the anatomical structures.

The high-fidelity simulation provided high-fidelity cues that allowed the learner to perform the same tissue manipulations as they could in the operational environment. Hence, the high-fidelity cues were relevant to the skills targeted for transfer which resulted in greater skills transfer effectiveness.

Critical Threshold of Fidelity

As established in the previous section, increased fidelity in cues relevant to the skills targeted for transfer often does increase transfer effectiveness. There are, however, some instances where increased fidelity in such relevant cues did not result in increased skills transfer. A closer examination of some of these cases indicates that the relationship between transfer effectiveness and simulation fidelity may not be linear. Lintern & Garrison (1992) provide an illustrative example of this.

A supplemental analysis of the data from Lintern & Garrison's (1992) study indicated that high-fidelity in elements of fidelity that provided cues relevant to the skills targeted for transfer leads to increased transfer effectiveness. Lintern & Garrision's (1992) study also indicated that this increase in skills transfer with increased fidelity only holds to a certain point, and that further increases in fidelity beyond this critical threshold of fidelity do not yield any further increases in skills transfer.

Lintern & Garrision (1992) studied the effect of visual field fidelity on the transfer of skill in performing crosswind landings. This is a motor-tacit skill in that it relies heavily on tacit knowledge, (i.e., the visually detected spatial relationships between the objects in the field of view), (Transport Canada, 2004). The study varied the level of physical-static fidelity by using three different levels of visual detail. This physical-static fidelity provided tacit knowledge relevant to the task; hence, the high-fidelity cues were relevant to the skill targeted for transfer.

Lintern & Garrison (1992) found that simulation-based training carried out at the lowest level of visual fidelity had no effect on skill transfer, but that training carried out at the higher levels of visual fidelity did result in improved skills transfer. Further, they found that there was no difference in skills transfer effectiveness between the medium visual fidelity simulation and the high visual fidelity simulation. The difference in effectiveness between the low-fidelity simulation and the medium-fidelity simulation is a very strong indication that increased fidelity can lead to improved skills transfer effectiveness provided the increased fidelity is in elements relevant to the skills targeted for transfer. The lack of significant difference in effectiveness between the medium and high-fidelity simulation indicates that the relationship between increased fidelity and increased transfer effectiveness is not linear; increased fidelity will result in increased transfer effectiveness only up to a certain point, but once fidelity has exceeded this critical threshold no further improvements in transfer effectiveness will be gained.

This relationship could be explained by considering the relationship between cognitive fidelity and all other elements of fidelity; namely that all other elements of fidelity exist to produce cognitive fidelity. Recalling that cognitive fidelity is the simulation's ability to induce the same mental processes in the learner as the operational environment would, it may be that this desired state of cognitive fidelity is achieved when levels of the other elements of fidelity reach this critical threshold.

The idea that there is a critical threshold of fidelity beyond which increases in fidelity do not result in increased transfer effectiveness was reinforced by Westra et al. (1986). Westra et al. (1986) varied the physical-static fidelity of the simulation by using different levels of visual detail, much like Lintern & Garrison (1992) did. They found that there was no increase in skills transfer effectiveness between the low-fidelity simulation and the high-fidelity simulation. An initial reading of this result would indicate that there is no relationship between the element of fidelity which was varied and the transfer of the target skill. However, the fact that Lintern & Garrison (1992) already demonstrated a link between teaching landing and visual fidelity suggests the underlying explanation is more complex. The results of Westra et al. (1986), when viewed through the lens of a critical threshold of fidelity, can be explained by the levels of fidelity within both simulations being on the same side of the critical threshold; i.e., either the fidelity of the low-fidelity simulation wasn't low enough or the fidelity of the high-fidelity simulation wasn't high enough to make a difference.

Walker (2014) also gives us a potential example of how fidelity must be above a critical threshold in order to result in improved skills transfer. Walker (2014) studied the effect of greater physical-haptic fidelity by the use of a motion seat when teaching dynamic flight manoeuvres to fighter pilots. Walker found that the motion seat provided no greater training effectiveness. The haptic cues the seat provided, such as acceleration and the vestibular sense of rotation, are important cues which pilots use to accomplish dynamic manoeuvres (Transport Canada, 2004). In this case the high-fidelity elements of the simulation were related to the targeted skills and should have shown results. The fact that these results failed to materialize may be another example of the fidelity being below the critical threshold.

A motion seat provides some haptic cues to the learner by using pneumatic cushions to simulate the acceleration forces a learner would feel on their back and buttocks as well as some very limited motion to simulate the vestibular cues a learner would experience in the operational environment. While the motion seat is able to mimic more of the operational cues than a static non-motion seat, it still cannot replicate the full range of haptic cues found in the operational environment; it cannot mimic the effects of sustained rotation, it cannot mimic the effects of sustained acceleration. In other words, the motion seat provides a symbolic representation of the haptic cues much like Lintern & Garrison's (1992) extremely low fidelity visual cues provided a symbolic representation of the visual environment. The motion seat had greater fidelity than the static seat, but the cues it provided were not realistic enough for the learner to associate them with the actual cues from the operational environment. The haptic fidelity of the motion seat was not sufficient to induce the required cognitive fidelity in the learner; i.e. the fidelity of the motion seat was below the critical threshold.

As with Walker (2014), the majority of studies (Martin & Waag, 1978a) (Martin & Waag, 1978b) (Woodruff et al., 1976) which examined the use of motion cues (physical-haptic fidelity) in aviation simulation-based training found that motion cues gave no significant increase in skills transfer effectiveness over simulators with no motion cues. This result is surprising given that the vestibular and proprioceptive cues a pilot receives in actual flight are crucial inputs for the pilot's control process. The physical-haptic fidelity provided by the motion cues is very much relevant to the transfer of motor-tacit skills required to control an aircraft. The motion cues should have helped.

A detailed look at the motion cues provided, and an application of the concept of a critical threshold of fidelity could explain these unexpected results. The simulators used in the studies reviewed were not able to perfectly replicate all of the proprioceptive cues found in the real aircraft. This lack is most pronounced in the simulator's inability to replicate the vestibular cues caused by the sustained rotation found as an aircraft turns and the magnitude of the forces the pilot experiences, (colloquially referred to as "G") when an aircraft accelerates or changes direction. Put in the simplest terms, while the simulator does provide some vestibular and proprioceptive cues, these cues are of extremely low fidelity. It may be that these cues are of such low fidelity that they are below the critical threshold of fidelity which would explain why they failed to produce any increase in skill transfer.

Denadai et al. (2012) may give some support to the concept of a critical threshold of fidelity. Denadai et al. (2012) studied transfer effectiveness of suturing skills learned by practicing on vinyl film, (low-fidelity), and pig skin, (high-fidelity), and compared them to a control group that had received only didactic training. They found that both forms of simulation gave significantly better transfer effectiveness when compared to the control group, but that the high-fidelity simulation did not show significantly greater transfer effectiveness when compared to the low-fidelity simulation. Suturing is a motor-tacit skill. Proper suturing requires the needle to be placed through the correct positions in the tissue and the correct direction and level of tension to be placed on the suture (Zenn, 2013). This makes suturing a cognitive-procedural skill with significant portions of motor-tacit skills. Proper transfer of this skill requires that the simulation provide sufficient visual cues for the learner to be able to place the needle in the correct place and that the model provide sufficiently realistic resistance to needle and suture passage that the learner develops the correct tacit knowledge regarding the direction and magnitude of tension to apply to the suture. These requirements translate into physical-static, (visual cues), and physical-haptic, (providing the correct amount of resistance to needle and suture passage), fidelity.

The pig skin is of higher physical-static fidelity in that it looks like skin. We have established that physical-static fidelity provides relevant cues for the learner, therefore, the visual appearance of the pig-skin should have produced superior transfer compared to that of the vinyl. The fact that it did not, when combined with the fact that both simulations provided superior transfer to the control group, suggests that both simulations were on the same side of the critical threshold for fidelity.

Grober et al. (2004) found similar results to Denadai et al. (2012) when they compared the effectiveness of low-fidelity simulation, (a piece of silicone tubing), and high-fidelity simulation, (a live rat *vas deferens*), against a control group, (didactic training alone), for the transfer of microsurgical skills. The high-fidelity simulator had greater physical-static fidelity in that it was living tissue and hence more closely resembled the operational environment. There may, or may not, have been differences in physical-haptic fidelity between the two simulators. No source could be found which compared the feel of suturing silicone tubing vs the feel of suturing live rat *vas deferens*.

The study evaluated learners' surgical technique using both procedural checklists, overall global rating scales as applied by expert raters and an evaluation of how well the learner's final product functioned. The surgical technique checklists evaluated the learners' ability to carry out a series of motor and cognitive steps. In other words, the checklists evaluated the learners' skill from a motor-tacit and cognitive-procedural skill standpoint. Motor-tacit skills rely on physical-static, (visual cues), and physical-haptic, (force feedback cues in response to the needles passage through the tissue) cues. The study found that learners trained on both the low and high-fidelity models showed significant more effective skill transfer on the checklist evaluation and global ratings than did the learners trained via didactic only methods. This indicates that simulation training led to increased transfer effectiveness. However, the study showed that there was no significant difference in transfer effectiveness between the high-fidelity simulation and the low-fidelity simulation. There was a difference in the physical-static fidelity between the two simulations, and hence there should have been a difference in the transfer effectiveness of the two simulations. The fact that there was not is further indication of a critical fidelity threshold, and that both of these simulations were on the same side of that threshold.

The final evaluation Grober et al. (2004) did of their learners provides an interesting data point. The final evaluation was carried out on the *vas deferens* of a sedated, live rat. Rats have two *vas deferens* and the learners performed an anastomosis, (reconnection of a severed vessel), on both of them. The first *vas deferens* was removed from the rat and the anastomosis was tested for function by passing fluid through it and looking for blockage or leakage. It was found that the learners who trained on the high-fidelity simulation had significantly better results on this test than did the learners who trained on the low fidelity simulation (silicone tubing). In other words, the learners who trained on the high-fidelity simulation were better able to perform the operational task. The fact that the checklist and global ratings scores indicated that there was no difference in transfer effectiveness between the two simulations is at odds with the final functionality test. This may be explained by differences in physical-haptic fidelity, (the resistance of the tissue to the passage of the needle, the amount of force required to properly tie a suture etc.), which would reinforce the concept of a critical threshold of fidelity. It is likely safe to assume that the silicone tubing and the live rat deferens have similar but different resistance to needle passage and other haptic cues, i.e., they have different physical-haptic fidelity. In this case, the physical-haptic fidelity of the silicone tubing was below the critical threshold and it was not as effective for skills transfer.

Of even greater interest is that Grober et al. (2004) left the other *vas deferens* in the rat for a further thirty days in order to test the long-term functional effectiveness of the procedure. It was found that there was no difference between the immediate functionality of the anastomosis and the functionality of the anastomosis at the 30-day mark for the learners trained on the high-fidelity simulation. However, the effectiveness of the anastomosis at the 30-day mark for the learners trained in the low-fidelity simulation was significantly improved over the initial functionality test and was not significantly different from the functionality of the anastomosis performed by the learners trained in the high-fidelity simulation. It is important to note that the *vas deferens* used for the 30-day test was the second one the learners operated on in the final evaluation. The improved functionality could be due to biological processes, or it could be due to increased skill gained while performing the procedure on the first *vas deferens* during the final evaluation. If the second case is true it would indicate that the fidelity in excess of the critical threshold is highly effective at increasing skill transfer in that only one attempt at the task at this increased level of fidelity resulted in significantly improved skill transfer. Again, this position is speculative and far from conclusive, but it does provide an indicator for potential future research.

Section Summary

Predicting the effect that simulation fidelity will have on skills transfer effectiveness requires a detailed examination of exactly which elements and aspects of a simulation are high-fidelity and comparing those elements and aspects to the cues which are relevant to the skills targeted for transfer. There is clear evidence that high-fidelity in cues which are irrelevant to the skills targeted for transfer will not increase skills transfer effectiveness.

There is also evidence that overall simulation fidelity involves more than just the fidelity of the physical simulator. In the majority of the cases examined, it appeared that a simulation with low-fidelity simulator equipment could achieve skills transfer effectiveness equivalent to that of a simulation with higher fidelity simulator equipment provided the low-fidelity simulation provided the same information as the high-fidelity simulation via an alternate means, (such as a facilitator directly telling the learners what cues were present).

There is evidence indicating that increased fidelity in cues relevant to the skills targeted for transfer will increase skills transfer effectiveness. There are also indications that there may be a critical threshold for fidelity. Fidelity which is below this critical threshold does not result in improved skills transfer effectiveness. While fidelity that exceeds this threshold does appear to result in improved skills transfer effectiveness, the relationship appears to be non-linear in that fidelity in excess of the critical threshold does not produce any greater skills transfer effectiveness than fidelity which just meets this threshold. The literature from which these two conclusions were drawn is sparse, which makes these conclusions speculative as opposed to definitive. This is an area which merits future research.

Conclusion

In answer to research question one, "What professional fields use simulation-based training and what skills is it used to teach?" the professional fields that use simulation-based training are listed in Table 3. The skills they use simulation-based training to teach can be described using the taxonomy: motor-tacit, cognitive-procedural, cognitive-pattern recognition, cognitive-problem solving and social-transaction. The frequency with which these skills appeared in the literature produced by each professional field, along with the first level categories used to develop this taxonomy can be found in both Table 3 and Appendix 1. The review of the professional fields which use simulation-based training to teach job related skills found in this paper includes only those professional fields and skills for which literature was found. It is possible that some skills or professional fields were missed either due to the search method used for this paper or because no literature was produced by those professional fields or concerning those skills. This is an area that merits further research.

In answer to research question two, “What constitutes fidelity within simulation-based training?”: the elements of fidelity within simulation-based training can be described using the taxonomy developed here: cognitive fidelity, physical-static fidelity, physical-haptic fidelity, functional-model fidelity, functional-situational fidelity and functional-social fidelity. Cognitive fidelity refers to how closely the learner’s cognitive activity in the simulated environment mimics the learner’s cognitive activity in the operational environment. The simulation-based training designer has no direct control over cognitive fidelity. The simulation-based training designer has direct control over the other elements of fidelity and must use them to achieve cognitive fidelity in the learner.

The taxonomy for skills taught via simulation-based training developed in answer to research question one provides tools for designers of simulation-based training to parse the overall tasks they are trying to train into individual skill categories. Identifying the skill categories targeted for training should aid designers of simulation-based training in identifying what types of fidelity, as described by the taxonomy for fidelity in simulation-based training developed in answer to research question two, will provide the most relevant cues for learners. Identification of the cues most relevant for learning will allow the designers of simulation-based training to focus effort and resources on only those aspects of fidelity which enhance skills transfer, thus optimizing the use of resources.

As was noted in the introduction, and elaborated on in the body of this paper, each professional field has its own nomenclature for describing fidelity within simulation-based training. This lack of standardized nomenclature inhibits the flow of information amongst the practitioners of simulation-based training. The taxonomies developed in this paper have applicability across multiple professional fields, and as such, could serve as a standardized nomenclature which would facilitate the flow of information among practitioners of simulation-based training. The use of these taxonomies would make it easier for practitioners of simulation-based training to learn from the experiences of their counter-parts in other professional fields.

In answer to research question three, “What is the detailed relationship between skill transfer and the elements of fidelity in simulation-based training?”: the skill transfer effectiveness of a simulation depends on the fidelity of the cues related to the skills targeted for transfer. High-fidelity in cues not relevant to the skills targeted for transfer does not result in increased skills transfer effectiveness. High-fidelity in cues relevant to the skills targeted for transfer may result in increased transfer effectiveness provided the information provided by those cues is not available from some other component of the simulation and the fidelity of those cues crosses the critical threshold of fidelity. While there are indications in the literature that a critical threshold of fidelity may exist, the evidence is far from definitive. This concept requires further research.

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Appendix A

Material Examined to Develop a Taxonomy for Skills Taught via Simulation-Based Training

Study	Professional Field	1st Level Code	2nd Level Code
Adams et al. (2015).	Medicine	Medical Treatment Management	Cognitive-Pattern recognition, Cognitive-Procedural
Ahad et al. (2011).	Medicine	Clinical Motor Skills, Clinical Procedural Skills	Motor-Tacit, Cognitive-Procedural
Alinier et al. (2006).	Medicine	Medical Treatment Management, Medical Diagnostic Skills	Motor-Tacit, Cognitive-Pattern Recognition, Cognitive-Procedural
Andersen et al. (2015).	Medicine	Clinical Motor Skills, Clinical Procedural Skills	Motor-Tacit, Cognitive-Procedural
Aronsson et al. (2019).	Aviation, Military, Industrial, Maritime	Team Management, Operational Training, Novel Problems, Process Control, Situational Assessment	Cognitive-Pattern Recognition, Cognitive-Procedural, Cognitive-Problem Solving, Social-Transaction
Bakken & Gilljam (2003).	Military	Resource Deployment	Cognitive-Pattern Recognition, Cognitive-Problem Solving
Beaubien & Baker (2004).	Medicine	Team Management	Social Transaction, Cognitive-Procedural, Cognitive-Problem Solving
Bennell et al. (2007).	Emergency Personnel	Operational Training	Motor-Tacit, Cognitive-Procedural
Bruschetta et al. (2021).	Driving	Flight-Control Manipulation	Motor-Tacit

Chellali et al. (2016).	Medicine	Clinical-Motor Skills, Clinical Procedural Skills	Motor-Tacit, Cognitive-Procedural
Coghill (1971).	Management	Team Management	Social Transaction
Corroenne et al. (2021).	Medicine	Clinical Motor Skills, Clinical Procedural Skills	Motor-Tacit, Cognitive-Procedural
Crichton (2017).	Medicine, Aviation, Industrial	Process Control, Response to Abnormal Situation,	Cognitive-Pattern Recognition, Cognitive-Procedural, Cognitive-Problem Solving
Curran et al. (2014).	Medicine	Clinical Motor Skills, Clinical Procedural Skills	Motor-Tacit, Cognitive-Procedural
Dankelman (2008).	Medicine	Clinical Motor Skills	Motor-Tacit.
Danylenko (2019).	Maritime	Procedures Trainer	Cognitive-Pattern Recognition, Cognitive-Procedural
De Witte et al. (2021).	Medicine	Clinical Motor Skills, Clinical Procedural Skills	Motor-Tacit, Cognitive-Procedural
Denadai et al. (2014).	Medicine	Clinical Motor Skills, Clinical Procedural Skills	Motor-Tacit, Cognitive-Procedural
Drew & Davidson (1993).	Management	Resource Deployment, Team Management	Cognitive-Problem Solving, Social Transaction
Elliott et al. (2007).	Management	Resource Deployment	Cognitive-Problem Solving
Epps et al. (2013).	Medicine	Clinical Motor Skills, Clinical Procedural Skills	Motor-Tacit, Cognitive-Procedural

Eslahpazir et al. (2014).	Medicine	Clinical Motor Skills, Clinical Procedural Skills	Motor-Tacit, Cognitive Procedural
Evgeniou & Loizou (2013).	Medicine	Clinical Procedural Skills, Clinical Motor Skills, Team Management	Motor-Tacit, Cognitive-Procedural, Social Transaction
Fauquet-Alekhine et al. (2015).	Industrial	Process Control, Response to Abnormal Situation,	Cognitive-Pattern Recognition, Cognitive-Procedural
Feinstein & Yager (2018).	Emergency Personnel	Provider-Client Interaction, Response to Abnormal Situation	Social Transaction
Fernández-Ávila et al. (2018).	Medicine	Medical Diagnostic Skills	Motor-Tacit, Medical Diagnostic Skills
Finan et al. (2012).	Medicine	Clinical Motor Skills, Clinical Procedural Skills	Motor-Tacit, Cognitive-Procedural
Fischer & Barnabè (2009).	Industrial	Process Control	Cognitive-Procedural
Friedman et al. (2009).	Medicine	Clinical Motor Skills	Motor-Tacit, Cognitive-Procedural
Gandhi et al. (2014).	Medicine	Clinical Motor Skills, Clinical Procedural Skills	Motor-Tacit, Cognitive-Procedural
Gonzalez-Cota et al. (2013).	Medicine	Clinical Motor Skills, Clinical Procedural Skills	Motor-Tacit, Cognitive-Procedural
Gonzalez-Navarro et al. (2021).	Medicine	Clinical Motor	Motor-Tacit
Granlund (2008).	Management	Resource Deployment, Team Management	Cognitive-Pattern Recognition, Cognitive-Procedural

Grantcharov & Reznick (2008).	Medicine	Clinical Motor Skills, Clinical Procedural Skills, Medical Treatment Management, Team Management	Motor-Tacit, Cognitive-Pattern Recognition, Cognitive-Procedural, Social Transaction
Grober et al. (2004).	Medicine	Clinical Motor Skills, Clinical Procedure Skills	Motor-Tacit, Cognitive-Procedural
Gu et al. (2017).	Medicine	Team Management, Provider-Client Interaction	Social-Transaction
Hall (1989).	Aviation	Flight Control Manipulation	Motor-Tacit
Hall (2010).	Emergency Personnel	Resource Deployment, Novel Problem, Response to Abnormal Situations, Operational Trainer.	Cognitive-Pattern Recognition, Cognitive-Procedural, Cognitive-Problem Solving
Hartley et al. (2008).	Emergency Personnel	Resource Deployment,	Cognitive-Pattern Recognition
Hoadley (2009).	Medicine	Medical Treatment Management,	Cognitive-Pattern Recognition, Cognitive-Procedural
Hontvedt & Øvergård (2019).	Maritime	Flight Control Manipulation, Procedures Training, Operational Training, Response to Abnormal Situation, Crew Co-ordination	Motor-Tacit, Cognitive-Procedural, Cognitive-Pattern recognition, Social-Transaction
Howard (2013).	Medicine	Medical Diagnostic Skills, Medical Treatment Management	Cognitive-Pattern Recognition,

Jacobs (n.d.)	Aviation	Flight Control Manipulation, Procedures Trainer	Motor-Tacit, Cognitive-Procedural
Jenkins et al. (2011).	Management	Resource Deployment	Cognitive-Problem Solving
Jibri et al. (2021).	Medicine	Clinical Motor Skills, Clinical Procedural Skills	Motor-Tacit, Cognitive-Procedural
Johnson & Johnson (2014).	Medical	Medical Treatment Management, Clinical Motor Skills, Medical Diagnostic Skills	Motor-Tacit, , Cognitive-Pattern Recognition, Cognitive-Procedural
Katayama et al. (2019).	Medicine	Clinical Motor Skills	Motor-Tacit
Keys et al. (1996).	Military	Resource Deployment, Team Management	Cognitive-Pattern Recognition, Cognitive-Problem Solving, Social-Transaction
Kneebone et al. (2007).	Medicine	Medical Treatment Management, Clinical Motor Skills, Medical Diagnostic Skills, Team Management, Provider-Client Interaction	Motor-Tacit, Cognitive-Pattern Recognition, Cognitive-Procedural, Social Transaction.
Kreiser et al. (2020).	Medicine	Clinical Motor Skills, Surgical Procedural Skills	Motor-Tacit, Cognitive-Procedural
Kylesten & Nählinder (2010).	Military	Resource Deployment, Situational Assessment	Cognitive-Pattern Recognition, Cognitive-Procedural
LeBlanc et al. (2004).	Medicine	Clinical Motor Skills, Clinical Procedural Skills	Motor-Tacit, Cognitive-Procedural

Leclet & Weidenfeld (1998).	Management	Resource Deployment, Operational Training	Cognitive Pattern Recognition, Cognitive-Procedural, Cognitive-Problem Solving
Lee et al. (2008).	Medicine	Clinical Motor Skills, Clinical Procedural Skills, Medical Diagnostic Skills, Medical Treatment Management	Motor-Tacit, Cognitive-Pattern-Recognition, Cognitive-Procedural
Lintern & Garrison (1992).	Aviation	Flight Control Manipulation, Procedures Training	Motor-Tacit, Cognitive-Procedural
Lintern et al. (1989).	Aviation	Flight Control Manipulation, Procedures Trainer,	Motor-Tacit, Cognitive-Procedural
Lukosch et al. (2016).	Management	Resource Deployment	Cognitive-Problem Solving
Macchiarella & Mirot (2018).	Aviation	Operational Training, Procedures Trainer, Crew Co-ordination	Cognitive-Procedural, Cognitive-Pattern Recognition, Social Transaction
Macchiarella et al. (2008).	Aviation	Flight Control Manipulation, Procedures Trainer, Operational Trainer	Motor-Tacit, Cognitive-Procedural
Mahon (2007).	Aviation	Flight Control Manipulation, Procedures Training, Operational Training, Response to Abnormal Situation, Crew Co-ordination	Motor-Tacit, Cognitive-Procedural, Cognitive-Pattern Recognition, Social Transaction

Maran & Glavin (2003).	Medicine	Clinical Motor Skills, Clinical Procedural Skills, Medical Diagnostic Skills, Medical Treatment Management	Motor-Tacit, Cognitive-Pattern Recognition, Cognitive-Procedural
Martin & Waag (1978a).	Aviation	Flight Control Manipulation	Motor-Tacit
Martin & Waag (1978b).	Aviation	Flight Control Manipulation,	Motor-Tacit
McCauley (2006).	Aviation	Flight Control Manipulation	Motor-Tacit
Meusel et al. (2019).	Industrial	Process Control	Cognitive-Procedural
Micheli & Training analysis and evaluation group (Navy) Orlando. (1972).	Aviation	Flight Control Manipulation, Procedures Training	Motor-Tacit, Cognitive-Procedural
Miller (1954).	Aviation	Flight Control Manipulation, Procedures Trainer, Operational Trainer	Motor-Tacit, Cognitive-Pattern Recognition, Cognitive-Procedural
Morgan & Hegarty (2006).	Medicine	Clinical Motor Skills, Clinical Procedural Skills	Motor-Tacit, Cognitive-Procedural
Mutlu et al. (2019).	Medicine	Clinical Procedural Skills	Cognitive-Procedural
Myers et al. (2018).	Aviation	Flight Control Manipulation, Procedures Trainer, Operational Trainer	Motor-Tacit, Cognitive-Pattern Recognition, Cognitive-Procedural
Nicholson et al. (2013).	Aviation	Flight Control Manipulation,	Motor-Tacit

Nicolaides et al. (2020).	Medicine	Team Management, Provider-Client Interaction	Social-Transaction
Noble (2002).	Aviation	Flight Control Manipulation, Operational Training, Procedures Trainer,	Motor-Tacit, Cognitive-Pattern Recognition, Cognitive-Procedural
Norman et al. (2012).	Medicine	Clinical Motor Skills, Clinical Procedural Skills, Medical Diagnostic Skills, Medical Treatment Management	Motor-Tacit, Cognitive-Pattern Recognition, Cognitive-Procedural
Pedersen et al. (2017).	Medicine	Clinical Motor Skills, Clinical Procedural Skills	Motor-Tacit, Cognitive-Procedural
Perez-Bennett et al. (2014).	Management	Resource Deployment	Cognitive-Problem Solving
Powell et al. (2008).	Emergency Personnel	Novel Problems, Resource Deployment	Cognitive-Pattern Recognition, Cognitive-Problem Solving
Rehmann et al. (1995).	Aviation	Flight Control Manipulation, Operational Training, Procedures Trainer,	Motor-Tacit, Cognitive-Pattern Recognition, Cognitive-Procedural
Reweti et al. (2017).	Aviation	Procedures Trainer	Cognitive-Procedural
Richard & Parrish (1984).	Aviation	Flight Control Manipulation	Motor-Tacit
Rocklyn et al. (1975).	Military	Operational Training, Resource Deployment	Cognitive-Pattern Recognition, Cognitive-Procedural
Rodgers et al. (2009).	Medicine	Medical Treatment Management	Cognitive-Pattern Recognition, Cognitive-Procedural

Romme (2003).	Management	Resource Deployment, Novel Problems	Cognitive-Pattern Recognition, Cognitive-Problem Solving
Sabbagh et al. (2012).	Medicine	Clinical Motor Skills	Motor-Tacit
Sencila et al. (2020).	Maritime	Response to Abnormal Situation, Operational Training, Team Management	Cognitive-Pattern Recognition, Cognitive-Procedural, Social Transaction
Stouten et al. (2012).	Management	Novel Problem	Cognitive-Problem Solving
Tu et al. (2015).	Driving	Flight-Control Manipulation	Motor-Tacit
Tuzer et al. (2020).	Medicine	Clinical Motor Skills, Clinical Procedural Skills	Motor-Tacit, Cognitive-Procedural
Wahl (2020).	Maritime	Team Management	Social Transaction
Walker & Thrasher (2013).	Medicine	Clinical Motor Skills, Clinical Procedural Skills, Medical Diagnostic	Motor-Tacit, Cognitive-Procedural, Cognitive-Pattern Recognition
Walker (2014).	Aviation	Flight Control Manipulation, Procedures Training	Motor-Tacit, Cognitive-Procedural
Wei et al. (2018).	Emergency Personnel, Military	Marksmanship	Motor-Tacit
Westra et al. (1986).	Aviation	Flight Control Manipulation, Procedures Training	Motor-Tacit, Cognitive-Procedural

Windrim et al. (2014).	Medicine	Clinical Motor Skills, Clinical Procedural Skills	Motor-Tacit, Cognitive-Procedural
Woodruff et al. (1976).	Aviation	Flight Control Manipulation, Procedures Trainer	Motor-Tacit, Cognitive-Procedural
Yovanoff et al. (2018).	Medicine	Clinical Motor Skills, Clinical Procedural Skills	Motor-Tacit, Cognitive-Procedural