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Knowledge structures for integrating working and learning: A reflection on a decade of learning technology research for workplace learning

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Abstract
Designing intelligent services for workplace learning presents a special challenge for researchers and developers of learning technology. One of the reasons is that considering learning as a situated and social practice is nowhere so important than in the case where learning is tightly integrated with workplace practices. The current paper analyses the experience of more than 10 years of research intending to offer intelligent services through capturing and leveraging knowledge structures in workplace learning. The reflection looks at results of several European research projects that have promoted this view. From this analysis, I arrive at a dichotomy of guidance versus emergence that describes how the technologies foregrounded one or the other, and what the effects of these design choices have been. I derive conclusions for dealing with this design trade-off in terms of conceptual, technological and empirical research.

Introduction

A significant amount of what we learn throughout our lives happens during and alongside work (Billett & Choy, 2013; Tynjälä, 2013). Research on how technologies impact learning at work has a long tradition in BJET. Despite its recognized importance, however, research in the journal seems to report mainly on learning in formal educational settings. An analysis of the content published in BJET between 2000 and 2005 resulted in the finding that only 3% of the publications analysed had been conducted "in colleges, industry and other training settings" (Latchem, 2006, p. 505). Only lately, a Special Issue was published in which the special potential that technologies have for creating new or enhancing existing learning situations at work was presented (Short & Greener, 2014).

In workplace learning, learning is tightly coupled with work practices and tasks, and a simplistic transfer of technologies used in formal educational settings seems to ignore some of the opportunities in integrating working and learning (Short & Greener, 2014). It is therefore important that the design of technology for workplace learning is informed by a social and situated perspective of learning that focuses on issues, such as the context in which learning takes place (eg,

Practitioner Notes

What is already known about this topic

- Intelligent systems for workplace learning often draw on knowledge structures that represent knowledge about the working domain.
- According to sociocultural theory, these knowledge structures can be said to emerge from human activity and guide learning and working.

What this paper adds

- I provide a systematization of previous research through a continuum of guidance versus emergence.
- This leads to an agenda for further conceptual, empirical and technological research in technology-enhanced workplace learning.

Implications for practice and/or policy

- When designing intelligent workplace learning systems, a trade-off needs to be considered that allows knowledge structures to be created and matured in workplace practices, and provide strong guidance for working and learning.

Gu, Churchill, & Lu, 2014), or the social and artefact-mediated character of learning (Tynjälä, Häkkinen, & Hämäläinen, 2014), to name just a few.

One of the important assumptions that has been brought forward by theories of social and situated learning is that artefacts that are used and created as part of these activities have an important role in mediating learning (eg, Engeström, 2001; Paavola & Hakkarainen, 2014). As an example, take the formalization of a business process that is used in a company to document the process of how an order of a particular type of customer is fulfilled. Such a formalization of the process mediates how several persons in the company work together to fulfil the order and what kind of information they exchange. The formalization of this business process (that might take the form of a chart drawing up the tasks and responsible persons, and a description of what needs to be done) is also used for onboarding new employees to teach them "how things are done around here." The business process description is likewise used when changes in the business processes are introduced. For example, when a new customer group is being addressed, then a team of employees might get together, revisit the description and discuss changes or adaptations of the business process.

This simplified example illustrates how the artefact (the business process description) mediates work, learning and knowledge creation. The assumption that has guided much of the work reported in this paper has been that it would be possible to support all these concerns within one overall conceptual and technological approach and allow for a true integration of working and learning.

For the purposes of the current paper, I restrict my view on just a subset of these artefacts created for and within workplace learning which I call "knowledge structures." These are knowledge representations that describe how significant concepts in a domain are interrelated. Examples that are typically considered in workplace learning are business process descriptions (such as in the example above), domain vocabularies and taxonomies, descriptions of competencies and their interrelationship, social networks and similar formalizations.

One of the reasons of the special focus on knowledge structures is their significance in intelligent systems used in workplace learning contexts. For example, taxonomies are used to structure complex hypermedia collections. Recommender systems for learning are built on top of domain ontologies, and performance support systems use business process descriptions to guide and support people working on tasks. A previous review of the field of educational technology conducted twenty years ago in BJET (Ely, 1999) predicted that we would be entering an era where "sophisticated hypermedia dialogue techniques will be applied in using artificial intelligence and expert systems" (p. 309). As knowledge structures can in fact be considered one of the cornerstones of these expert systems employing AI, it is of some relevance in the field to review how such knowledge structures have been employed, and whether they have been successful in fulfilling the vision set 20 years ago.

The purpose of this paper therefore is to reflect on a decade of attempts to realize the vision of integrating learning and working by utilizing knowledge structures in intelligent ICT systems for workplace learning. From reviewing a set of rather diverse approaches and results, a major design trade-off has emerged that describes one of the main challenges in workplace learning. It describes a situation where one tries to support guiding novices, and at the same time support the emergence of new knowledge in a group of experts.

In the next section, I will briefly review some of the theories that have motivated the approach. After that, three large-scale international projects will be presented that have taken some steps to realizing the vision. In closing, I will reflect on the success of this endeavour and where we stand in terms of conceptual models, technology and empirical research.

The role of knowledge structures in workplace learning

Knowledge structures

The term "knowledge structure" was established in the 1970s as a key concept in "cognitive science," an emerging discipline that was established at the intersection of psychology and computer science to contribute to an understanding of the working of the mind (Schank & Abelson, 1977). Hence, the term was conceived as boundary concept that could represent both human knowledge and those structures that would be operated by intelligent machines (AI).

In education, knowledge structures were defined as the knowledge of how concepts in a domain are interrelated (Jonassen & Wang, 1993). In intelligent educational systems, these structures were utilized, for example, to adapt navigation (eg, in adaptive educational hypermedia) or to provide knowledge tracing, adaptive assessment and information presentation, or learner guidance (in intelligent tutoring systems). Knowledge structures are also important in conceptions of workplace learning where they present different structural components of the organizational knowledge base. They include not only relationships between important concepts of an organization (such as about technology, marketing, production), but also representations of goals, beliefs or generally a "mental template that individuals impose on an information environment to give it form and meaning" (Ahuja & Novelli, 2015, p. 552). These can reside in physical or electronic media, but also in organizational members or routines.

Due to their origin in cognitive science, knowledge structures in workplace learning have predominantly been applied in systems following a cognitive information processing account of learning, or learning approaches that follow the "knowledge acquisition metaphor" (Paavola, Lipponen, & Hakkarainen, 2004). Numerous examples exist in which expert systems have been created using knowledge structures in the form of concept hierarchies or domain ontologies, to structure content and facilitate information access, perform assessment, guide training or task performance, or offer expert advice (eg, in the medical domain). More examples can be found in a recent review (Ruiz-Calleja, Prieto, Ley, Rodriguez-Triana, & Dennerlein, 2017), and this review also confirms that most systems follow the knowledge acquisition metaphor. In these cases, knowledge structures are usually modelled according to the view of an expert, and learners are assumed to acquire that expert knowledge.

This individualistic view of learning has been challenged in the workplace learning domain, just the same as in formal learning. Models of distributed cognition assume that cognitive activity is distributed across internal and external representations and the latter are created to offload part of that activity (Hollan, Hutchins, & Kirsh, 2000). So in the example of the business process representation mentioned in the beginning of the paper, the external representation is created and maintained in order to make it easier for people to retrieve from their memory what needs to be done in particular steps, where to find important information and how to process that information. Also, the process representation plays an important role in coordinating work of different people, so that cognitive activity gets further distributed across several persons as well. Hence material, mental and social structures interact in human activity (Hollan *et al.*, 2000), and material structure functions as an intermediary to cue and trigger behaviour in collaborative working settings (Kump, Moskaliuk, Cress, & Kimmerle, 2015).

In a similar way, theories of sociocultural learning assume that all human activity is mediated by artefacts and that human cognition is inseparably connected to these artefacts by processes of externalization and internalization. In this sense, the artefact (such as a knowledge structure) can become internalized, as in the case where an expert is not dependent any more on the external representation of the business process when performing her work, but her activities would still be mediated by that artefact. Sociocultural learning theory assumes that such "scaffolds" exist first in the social domain where they guide the learning of novices, before they get personal through internalization when they guide expert behaviour (Billett, 2002).

These theories also explain how artefacts come into existence. In this view, artefacts are a natural by-product of human culture and its development. In an attempt to solve important problems, communities create artefacts, which guide learning and working and are being transmitted through cultural processes. Several theoretical accounts have shaped thinking in this direction, such as communities of practice (Wenger, 2004), activity theory and trialogical learning (Paavola & Hakkarainen, 2005), knowledge building (Scardamalia & Bereiter, 2003), meaning making (Stahl, 2004) and others.

The guidance versus emergence continuum

One can generally distinguish two situations of how knowledge structures or other artefacts are used in workplace settings (see, eg, Collis & Winnips, 2002). On the one hand, these structures *emerge* from activities and practices of a community. At the same time, it is assumed that these structures are *used for guiding learning* in that same community. The latter is often connected to conceptions of "learning as participation" (Paavola & Hakkarainen, 2014), where it is assumed that learning happens by appropriating the shared norms, values and practices of a community. Billett (2002) has provided a detailed account of how guidance happens through the participation in work practices either directly provided by more experienced co-workers or indirectly through the use of workplace artefacts, and learners thereby progressively acquire higher levels of competence.

On the other hand, those artefacts are also *created and maintained* by the community. These creative forces have been considered in different theories of "knowledge creation," such as trialogical learning, knowledge building or knowledge maturation. Paavola and Hakkarainen (2014) discuss these theories to highlight "collaboratively developed artefacts and objects and associated collaborative practices (…) when developing theories of learning." (p. 60)

In workplace learning, these two aspects (guidance and emergence) are usually seen as fundamentally different learning situations. Guidance is usually covered through formal training, employing course management systems, or through guiding work processes through performance support systems (Wild, 2000). Emergence is usually considered as a knowledge creation and management challenge, and various knowledge management or collaboration systems are used, including social media, such as wikis. In the knowledge maturation model (Maier & Schmidt, 2014; Schmidt *et al.*, 2009), these two situations are considered as being situated in different levels of maturity: guidance happens when knowledge is mature and widely agreed, while emergence happens in situation where knowledge is not mature and agreement is not yet reached. Figure 1 shows some of the differences between the poles.

Three cases of the use of knowledge structures in workplace learning

I will now present three large-scale R&D projects that have been funded under the EU frameworks on technology-enhanced learning (TEL). The projects were selected as typical examples of the use of knowledge structures in intelligent systems for workplace learning. They were selected as they represented typical perspectives in workplace learning in the European TEL agenda at the time. Besides these three examples, I also discuss related projects, mostly also funded under the same framework to complement the picture (for a list of all projects mentioned in this paper, see the Appendix). My intention is not to present the projects in their entirety, but instead I will focus on results pertaining to how knowledge structures emerge in common activity and how these are then used in guiding learning.

APOSDLE—Process-oriented and self-directed learning (2006–2010)

The *APOSDLE* project influenced much of the agenda of the following projects in that it quite clearly set its objective to bridge the gap between working and learning. Taking the departure from cognitive apprenticeship models of learning, the project saw learning as a situated passing on of knowledge and skills in working situations. This happened either by identifying helpful documents that could be used for learning or by identifying experts to talk to. Following the idea of adaptive learning systems, recommenders were triggered from an understanding of the context of the individual learner (eg, which task the learner was dealing with). In *APOSDLE*, this led to a definition of *competencies* as the common denominator between work and learning. The main learning settings were in consultancy work as well as in engineering.

Knowledge structures

Several knowledge structures were used in the *APOSDLE* system, and modelling methodologies and tools were provided to instantiate the models in a particular domain. The "domain model" consisted of a collection and hierarchical structuring of the most important concepts of the working domain. Second, a "task model" described the typical tasks that had to be performed by the workers. Third, a "competency model" turned the domain model into a model of the individual capabilities that were needed to perform the tasks. Moreover, several mapping and annotation

Guidance	⟷	**Emergence**
Learning as adaptation to knowledge and practices	**Key Learning Principles**	Learning as collaborative creation of new knowledge and practices
Teacher agency	**Agency**	Learner agency
Scaffolding, Cognitive Apprenticeship	**Theoretical approaches**	Knowledge creation and maturation
Given	**Knowledge structures**	Emerging
Ontologies, Adaptive Learning Technology	**Technological Choices**	Folksonomies, Collaborative Learning Technology

Figure 1: The guidance–emergence continuum and possible trade-offs when designing learning technology for workplace learning [Colour figure can be viewed at wileyonlinelibrary.com]

tools were created to map concepts of the domain model to tasks, or to document snippets so that they could be discovered (Ley *et al.,* 2008; Lindstaedt *et al.,* 2010).

Emergence versus guidance

The creation of the knowledge structure happened by means of the abovementioned modelling tools through a quite laborious process of discussing, modelling and validating within a group of domain experts. From a theoretical standpoint, this negotiation should help to create the models in line with the social learning theories: the resulting models represented a snapshot of the understanding of the community with regard to the conceptualization of the domain, their task and skills required. Once the models had been instantiated, they were fed into the system and remained stable until an update was provided. The models were then used for a number of guidance processes in the tradition of adaptive learning systems: they built user models (what skills a particular worker was likely to have or needed to learn, and who were the experts for that topic) (Ley & Kump, 2013; Lindstaedt, Beham, Kump, & Ley, 2009), they discovered co-workers or experts to discuss a particular topic (Beham, Kump, Ley, & Lindstaedt, 2010), or they retrieved materials helpful to tackle a particular task (eg, Ley, Kump, & Gerdenitsch, 2010).

Related approaches

Similar to *APOSDLE*, knowledge structures in other projects at the time were often lists or ontologies of competency descriptors that were meant to formalize the needed knowledge, skills or attitudes needed to perform in a job. These structures were used to guide learning either in the work context, such as in the case of the *PROLIX* project (Giorgini, Zimmermann, Faltin, & Vervenne, 2006), or in the transition from formal education to lifelong learning, such as in the projects *TenCompetence* or *CALIBRATE* (Koper & Specht, 2008; Van Assche, 2007). Competencies were meant to align training to the organizational requirements, and therefore decrease the training time needed for employees to be upskilled (Giorgini *et al.*, 2006). A related development in this time was a focus on *learning objects*, which were thought to be reusable, standardized and often open digital resources that could be combined to form units of learning and contributing to the widespread use for workplace learning (Sánchez-Alonso & Frosch-Wilke, 2005).

Results and reflections

The *APOSDLE* system is aimed more at the guidance side of the continuum. While the emergence of knowledge structures can be said to happen in the domain modelling phase, there is limited emergence of structures during use. The models were found useful for novices in the domain. Preference was given for awareness of important domain concepts and materials, as opposed to the more prescriptive form of guidance in the form of learning paths (Lindstaedt *et al.,* 2010).

MATURE—Social learning (2008–2012)

With the advent of Web 2.0 tools, the knowledge creation end of the spectrum became more prominent in the TEL research arena. The MATURE project was one of those projects that put the creation and further development of knowledge in working contexts very explicitly on the agenda. The project started from the assumption of "knowledge maturation," a goal-directed development of knowledge that is resulting from diverse organizational learning processes.

Knowledge structures

MATURE looked quite explicitly at the maturation of three types of organizational knowledge. First, task and process knowledge, second semantic structures of the knowledge domain and third content knowledge (which usually consisted of natural language texts) (Schmidt *et al.*, 2009). Typical examples were collections of tags that evolved into ontologies or wiki articles that over time became more refined and agreed. Several knowledge maturing services were developed that could operate on these structures, such as recommender services or quality indicators to measure readability of texts, and that would guide the further development and maturation of the structures (Weber *et al.*, 2009). At the front end, the learning tools often were meant to bridge situations in which the knowledge maturing process would get stalled, such as in the interaction of individuals generating ideas and communities that might take up these ideas.

Emergence versus guidance
The knowledge maturation model (Maier & Schmidt, 2014) made the first important step to realize that knowledge that emerges in human activity exists on different levels of maturity. In early stages of the maturation process, knowledge would be rather useful for experts, and at the more mature stages (where knowledge was more decontextualized and better structured), it would become more useful to guide novice learners. With this model, there was now a clear conceptual advance to integrate working and learning, and the expert and novice perspectives of workplace learning. However, the assumptions that differing maturity stages would support different levels of expertise were never really tested empirically, as most of the services developed were still at early stages.

Related projects
Similar to *MATURE*, the *KP Lab* project (Lakkala *et al.*, 2009) created spaces for collaboration and co-creation in workplace learning. Knowledge creation approaches were also addressed in the *PALETTE* project (Daele, Deschryver, Gorga, & Künzel, 2007), which took the perspective "communities of practice" and developed online environments and web services for knowledge management and learning. The resources shared in those communities were seen as the evolving memory. Important processes were agreeing on meaning of terms, the collective categorization, annotation and reuse of documents. Services were created for producing and sharing resources, for reification of different forms of knowledge and for collaborative learning. On the technological side, these projects were more concerned with the ontology generation process, rather than on automatization. Also, typical Web 2.0 technologies such as wikis and social tagging were used for knowledge creation.

Results and reflections
MATURE was more concerned with the emergence end of the continuum. It is also notable that MATURE, as well as all the other mentioned projects, put emphasis on the further development of theory. Sociocultural learning theory such as activity theory and communities of practice was brought to the fore, and dedicated models were suggested, such as knowledge maturation (Schmidt *et al.*, 2009) or trialogical learning (Paavola & Hakkarainen, 2014). The knowledge maturation model provided a suitable conceptual framework to describe how emergent structures would guide learning in workplace learning. However, it still proved to be difficult to support both emergence and guidance at the same time. The knowledge maturing services predominantly created awareness about levels of maturity or directed attention of the community to those parts of the structures that needed further work. Guiding individual learners was not central to the project.

Learning Layers—Scaling informal learning (2012–2016)
The central theme of the Learning Layers project was to scale informal learning at the workplace using adaptive and social learning technology, and embed learning into workplace practices using mobile technology (Ley *et al.*, 2014). In a sense, Learning Layers can be seen as an attempt to bring guidance again more to the foreground. The project tackled the challenge of drawing on peer production processes to generate learning materials, but at the same time supporting meaningful learning by scaffolding individual learners. The project also involved more diverse learners than the previous projects by involving novices (eg, apprentices in the construction

industry) as well as experienced professionals (eg, practicing doctors) in domains that had been slower to take up learning technology (construction and health care).

Knowledge structures

In line with the *MATURE* project, a focus was put on tags that could describe the learning and working domain and be used for discovering helpful materials. Tags were also seen as a way to negotiate the meaning of particular experiences and established shared understanding in a group of learners (Dennerlein, Seitlinger, Lex, & Ley, 2016). Several services made use of the tags produced, eg, recommender services for resources (Seitlinger *et al.*, 2015) or tag recommenders that were intended to drive the consistency of how objects were described (Seitlinger *et al.*, 2018).

Emergence versus guidance

The Learning Layers project can be seen as an attempt to overcome the divide between emergence and guidance. Materials were collected and described during work, allowing knowledge structures to emerge in a collaborative knowledge building process. At the same time, these materials were then shared and fed back to other learners who could make use of them during work. Examples were tools such as *Bits and Pieces* (Dennerlein *et al.*, 2014) and *KnowBrain* (Dennerlein *et al.*, 2015) to collect and share learning experiences during work, *Confer* to support progressive inquiry in group work (Treasure-Jones, Sarigianni, Maier, Santos, & Dewey, 2019), and *Living Documents* (Bachl, Zaki, Schmidt, & Kunzmann, 2014) to support collaborative editing of documents, and Social Augmented Reality to support guidance during work on site (Pejoska, Bauters, Purma, & Leinonen, 2016). All of these covered different aspects of the collaborative knowledge building process, and several of them were connected via a social semantic infrastructure called the *Social Semantic Server* (Ruiz-Calleja *et al.*, 2019).

Related approaches

The *Learn-B* environment was developed in the *Intelleo* project to support self-regulated learning (SRL) at the workplace. Some of the interventions offered through the system, such as the provision of usage information on resources in the system, or the recommendation of competences or learning goals or paths, can be considered to be based on emergent knowledge structures (Siadaty, Gašević, & Hatala, 2016). The *Charting Collective Knowledge* model proposed by Littlejohn, Margaryan, and Milligan (2012) is also situated in the self-regulated learning literature, and individual learning is seen as being influenced by collective knowledge (structures) to which individuals contribute.

Results and reflections

The *Learning Layers* project made an attempt to overcome the divide between emergence and guidance; however, the final proof of whether knowledge structures that have emerged in workplace activity can enhance learning of novices when fed back to learners has not yet been finally achieved. Nevertheless, a number of important results have been obtained along the way. These will be more systematically reviewed in the next section.

Overall reflections and discussion

Bridging the continuum of emergence and guidance, and delivering one integrated conceptual and technological solution to integrate working and learning, has proven to be a more daunting task than initially conceived. I will first list a few barriers that have been encountered along the way, and then, I will review the technological, conceptual and empirical results that were obtained despite these barriers.

Barriers of technology use for the integration of working and learning

Barriers focusing on adoption of technology in workplace learning have been discussed elsewhere in more depth (eg, Pawlowski *et al.*, 2014; Short, 2014), but here I want to focus especially on barriers related to the use of intelligent systems and knowledge structures in workplace learning. Some of these remind us of the specificities of workplace learning (as compared to formal education).

Addressing diverse target groups
Addressing experts and novices of a domain with one and the same system has proven to be a major challenge. A long tradition of research has shown that experts and novices have quite different approaches when it comes to learning (eg, Tynjälä, 2013), and two rather distinct research fields have been established that either focus more on the application of technologies in novice versus expert learning (educational technology vs. knowledge management). It may well be that it will prove to be unrealistic to address both target groups with one integrated system and that a more differentiated approach needs to be taken. It is clear from our research here that novices are in need of greater amount of scaffolding and that experts expect a larger degree of freedom when interacting with knowledge structures.

Contextual nature of knowledge and learning
Learning at the workplace often addresses domains that are highly specialized (such as health care or construction) and also develop quickly (Billett & Choy, 2013). Learning in these domains is dependent on the context where it takes place. Consequently, workplace learning researchers need to spend a significant time understanding constraints and opportunities of the domain, before learning interventions can be designed (Ley *et al.*, 2014). Also, knowledge structures need to reflect the realities of the complex and dynamic learning domains under study.

Technological advances
When looking at the decade of research that is described above, it is clear that technologies were quite different in 2006 than they are now. New technologies bring new opportunities, offer new affordances and also change paradigms of working and learning. An example is the emergence of Web 2.0 approaches that had a major impact on workplace learning research. More recently, learning analytics has started having an impact in the professional learning arena (Ruiz-Calleja *et al.*, 2017). By picking up on these trends, workplace learning research can benefit from growing interest and explore new solutions to old problems. However, this also means technology that is employed in research is not always as mature as it should be for wide adoption.

Difficulties in empirical research
Empirical research in technology-enhanced workplace learning faces a number of challenges. Small samples are usually a result of all barriers mentioned above. Because of the domain-specific character, the number of participants involved in such activity is usually small from the start. Second, learning is not their main concern which means that participants need to balance the priorities for using technology for learning with other responsibilities in their job. Less mature technology is another risk factor in adoption and evaluation. And finally, the highly contextual nature of learning and working makes controlling for unwanted effects difficult.

Where we stand: Conceptual progress

The reviewed projects have made important contributions to how knowledge structures for workplace learning technology connect learning more closely with workplace practices. Some have put more emphasis on how those structures guide learning, and others have considered how structures are created and developed further. In order to conceptually bridge emergence and guidance aspects, I have recently proposed the "knowledge appropriation model" to put these different concerns into a common conceptual framework (Ley *et al.*, 2019). It is an attempt to connect two related workplace learning processes: considering the emergence pole, *knowledge maturation* (Maier & Schmidt, 2014, left side of Figure 2) considers how knowledge is created through sharing, co-creation, formalization and standardization in a goal-directed systematic manner. The guidance pole is covered through *scaffolding* (right side of Figure 2) that describes an apprenticeship learning approach through which learners are guided towards appropriating negotiated knowledge (Billett, 2002; Hung & Chen, 2000). In both knowledge maturation and scaffolding, shared artefacts (such as knowledge structures) play a central role in mediating problem solving and learning as common activities. In both scaffolding and knowledge maturation, the use of these artefacts can be described by a set of knowledge appropriation practices (centre part of Figure 2): Learners are made aware of artefacts, and they build a shared understanding, and then adapt and validate knowledge in new situations. The model can be used to design technology to encourage creation and use of knowledge structures in workplace learning environments.

Where we stand: Technological results

Recently, Experience API (https://xapi.com/) has gained quite a large adoption in the learning technology and learning analytics community. However, this data model and the infrastructures built on it follow a rather individualistic understanding of knowledge. While it recognizes informal experiences as a source of learning, the event-focused character of knowledge representation does not very well allow to capture emergent knowledge structures.

As a complementary approach, the *Social Semantic Server* (SSS) interconnects diverse tools for knowledge building and learning (Ruiz-Calleja *et al.*, 2019). While the infrastructure is mainly motivated by knowledge creation theory (and hence stands more on the emergence side of our continuum), it is still capable of dealing with ontologies or other more stable conceptualizations. An example of the use of both tags and pre-established categories can be found in Dennerlein *et al.* (2016) where the SSS supported more exploratory and collaborative learning activity.

A very interesting further development in technological approaches for workplace learning lies in the integration of sensor streams originating from wearables that track physical behaviour (eg, tracking gaze, movements) or physiological reactions. Koren and Klamma (2018) present an engine called Social Web Environment for Visual Analytics developed in the *WEKIT* project. This allows to collaboratively create data pipelines and visualizations from those sensor streams. In principle, this would enable collaborative creation of knowledge structures for augmented training of physical skills in situ. Feedback is directly visualized, guides the learner and therefore connects conceptual knowledge with skilled behaviour.

Where we stand: Empirical research

Despite the barriers for empirical research on workplace learning technology discussed above, it is now feasible to study feedback processes where parts of knowledge structures that had

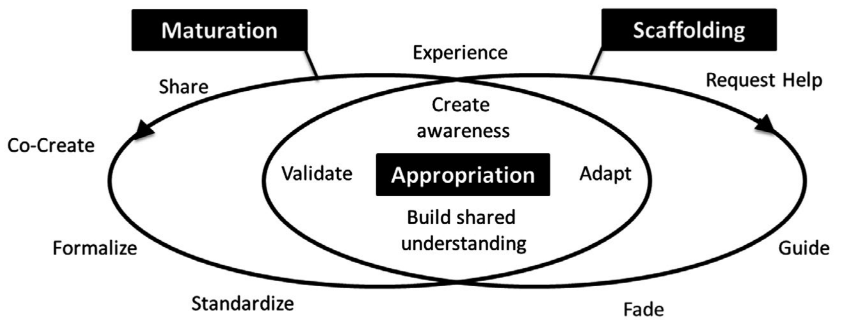

Figure 2: Knowledge appropriation model

emerged from realistic workplace activity support learners in aspects of their learning with some measurable effects. In the *Learning Layers* project, the use of *Confer* led to demonstrable effects on collaborative practices in several healthcare practices (Treasure-Jones *et al.*, 2019). However, the tool functionalities that led to these effects were not based on emerging structures, but rather designed into the tool (eg, scaffolds for progressive inquiry). Interventions triggered through the *Learn-B* environment developed in *Intelleo* had measurable effects on self-regulated learning as evidenced by multiple regression analysis (Siadaty *et al.*, 2016). Possible learning gains that resulted from using the system were not part of this analysis. In a study that used the Social Semantic Server, we found evidence that feeding back emergent tag networks in a work-integrated web curation scenario led to higher levels of shared understanding in the group. When recommending tags in such situation, these were more readily accepted, if the recommender services made use of the emerging category–tag relationship (Seitlinger *et al.*, 2018).

Conclusions and limitations

Despite these promising empirical results, we are still far from understanding how knowledge services that operate on emergent knowledge structures contribute to individual learning. It is unclear in which situations they work and in which they do not work, and how exactly they contribute to individual learning. The knowledge maturation model would predict that the degree of maturity of emerged knowledge would determine for whom (novices or experts) they would be especially helpful, but this prediction still needs to be empirically tested.

Moreover, what is understood as "knowledge" has been treated rather informally in this paper. The knowledge maturation model provides some insights into important *conceptual* knowledge that is created in a domain, such as semantic, procedural and content-based. However, there are certainly other types of knowledge that I have not addressed. For example, epistemic structures determine how professionals organize their inquiry in general, and what are accepted forms of knowledge. As an example, the progressive inquiry scaffolds mentioned in Section "Where we stand: empirical research" describe epistemic knowledge structures through which the healthcare professionals collaboratively create new knowledge. Epistemic structures can also be observed in reflective professional dialogues (Saucerman, Ruis, & Shaffer, 2017) or in how professionals seek and provide help in online forums (Pata, Santos, & Burchert, 2016). Such epistemic structures seem to be much more fundamentally embedded in the culture of the community, to change slowly and therefore more difficult to observe and model explicitly.

Despite those limitations, there is now a solid conceptual basis and a set of technologies ready to be deployed. And it now appears much more realistic than 10 years ago to conceive of intelligent AI solutions that consider human activity as a social and situated practice around shared artefacts that can be traced and supported in technology-enhanced workplace environments.

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Statements on open data, ethics and conflict of interest

Research projects that were reviewed have been listed in the Appendix, and open research data for the original studies are available through those links.

Ethics approval for the research conducted in healthcare institutions in the Learning Layers project was obtained from the University of Leeds School of Medicine Research Ethics Committee. No additional original data were obtained through this research.

I declare that no conflict of interest exists.

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Appendix A

Research Projects related to Workplace Learning funded under the "technology-enhanced learning" (TEL) programmes of the European Commission in FP6, in FP7 and partially in H2020.

Project acronym	*Programme*	*Years*	*Record on EU cordis repository*	*Project website*
PALETTE	FP6	2006–09	https://cordis.europa.eu/project/rcn/80599_en.html	http://palette.ercim.eu
PROLIX	FP6	2005–09	https://cordis.europa.eu/project/rcn/100253_en.html	–
APOSDLE	FP6	2006–10	https://cordis.europa.eu/project/rcn/80574_en.html	http://www.aposdle.tugraz.at/
TenCompetence	FP6	2005–09	https://cordis.europa.eu/project/rcn/80579_en.html	–
MATURE	FP7	2008–12	https://cordis.europa.eu/project/rcn/85448_en.html	http://mature-ip.eu/
Intelleo	FP7	2009–12	https://cordis.europa.eu/project/rcn/90619_en.html	http://www.intelleo.eu
MIRROR	FP7	2010–14	https://cordis.europa.eu/project/rcn/95667_en.html	–
ARISTOTELE	FP7	2010–13	https://cordis.europa.eu/project/rcn/95597_en.html	–
Learning Layers	FP7	2012–16	https://cordis.europa.eu/project/rcn/106430_en.html	http://learning-layers.eu
EmployID	FP7	2014–18	https://cordis.europa.eu/project/rcn/189121/factsheet/en	https://employid.eu/
LearnPAd	FP7	2014–16	https://cordis.europa.eu/project/rcn/189117/factsheet/en	http://www.learnpad.eu/
WEKIT	H2020	2015–18	https://cordis.europa.eu/project/rcn/200491/factsheet/en	https://wekit.eu/
DEVELOP	H2020	2016–19	https://cordis.europa.eu/project/rcn/200142/factsheet/en	http://www.develop-project.eu/