Technical Report

Ambient Learning Spaces (ALS)

Interactive Learning Environments and Knowledge Media Machines for Post-Constructivist Teaching and Learning in the 21st Century

Michael Herczeg

Michael.Herczeg@uni-luebeck.de

Institute for Multimedia and Interactive Systems (IMIS), University of Luebeck, Germany

Abstract: *Ambient Learning Spaces (ALS) is a platform to create, use, and manage digital teaching and learning environments. The concepts for ALS have been based on contemporary pedagogical theories in awareness that learning processes are going to be less dependent on teaching technologies and content and more on the active processes of learning itself. ALS has been developed over more than 15 years in a series of research projects. ALS enables individuals as well as groups of learners to create, share, distribute, and reuse semantically annotated media in social teaching and learning processes. The central component of ALS, the Network Environment for Multimedia Objects (NEMO), forms the media and logic backend for multimodal interactive frontend learning applications. It is a cloud-based repository and allows the creation of semantically annotated multimedia content to be used across all ALS learning applications. These ALS applications can be used on mobile, stationary, and immersive interactive systems such as domes, large screens, tangibles, mobiles, and wearables. Media content in form of text, image, video, or 3D can be reused and shared by different learning applications and will be adapted on the fly as needed for various interaction devices with different interaction modalities. Interaction methods depending on the available devices reach from direct manipulation interfaces on touch displays to mobile augmented reality and interactive 360° virtual reality applications. Plain media can be constructed into Knowledge Media by semantic markups. Through the ALS Portal, teachers and learners include, edit, annotate, and semantically model their own media. Special user interfaces like tangible media and large multi-touch screens as well as mobile media and wearables enable body- and space-related post-constructivist learning in real life contexts. ALS has been used in schools, museums, universities, biotopes, and urban spaces in pilot installations with different configurations, some of them being used in long-term studies over years.*

Purpose: *This is the final technical research report for giving a detailed overview about the vision, goals, methodology, technology, and studies performed over more than 15 years development and pilot installations of the ALS Project. Most of the content, especially the studies, can be found in more detail in the different publications referenced in the report.*

Keywords: *Ambient Learning Spaces, Learning Environments, Learning Platforms, Ambient Learning, Multimodal Learning, Knowledge Media, Mixed Reality, Post-Constructivist Learning*

Citation: Herczeg, M. (2024). *Ambient Learning Spaces (ALS) – Interactive Learning Environments and Knowledge Media Machines for Post-Constructivist Teaching and Learning in the 21st Century*, Technical Report TR-ALS-01-2024, IMIS, University of Luebeck, pp. 1-31.

Author: Prof. Dr. Michael Herczeg
Principal Investigator of the ALS Project

Published: 22.05.2024

The Vision and the Goals

While starting research in the area of digital learning around the year 2000 we designed, implemented, and studied several digital interactive multimedia learning systems. We observed that the various educational systems built were often solutions with low or even no abilities to be connected to each other. When working with children and youth, as well as school teachers and museum curators in real contexts, it proved to be a disadvantage that these independent systems were different in their interaction design. Aside from that, the media content collected, constructed, and stored by the learners in one system was not compatible and accessible from another system. This seemed to be appropriate for certain isolated tasks or small lab-based scientific studies but inappropriate and demotivating for the target users in real world contexts. So the idea and concept emerged to implement an integrated research platform and working pilot system for in-school and out of school contexts like museums, urban spaces, natural habitats, and other learning situations that was based on one central media repository (backend storage) with connected multimodal interactive learning modules (frontend applications) [1]. As different frontends using a large spectrum of current and emerging interaction devices, the backend storage needed to be capable of automatically adapt and deliver stored media to the requirements of the frontend applications. When we talk about teaching and learning another question comes naturally into view. It is about the relationship between media and knowledge, i.e. semantic modeling for media in a knowledge representation layer to connect to meaning. This concept has been called *Knowledge Media*. In the beginning we have been calling it *Multimedia-Enriched Learning Objects* [2]. Nevertheless, the vision and the goal have been to implement a kind of extendable multimodal interactive *Knowledge Media Machine*. We called it *Ambient Learning Spaces* (*ALS)*. As a result of the ubiquitous and always growing availability of digital devices, such a learning environment would have an *ambient nature,* embedding the users, here especially its learners and teachers[1], in a blended interactive environment of physical and digital objects [3].

The Project and this Report

The following technical research report will be describe and discuss how we transformed this vision into the evolutionary research platform and pilot system ALS with a broad variety of integrated interactive applications of different modalities that could be used and studied on a daily basis in real-world contexts. The work received long-term funding by the DFG (German Research Foundations) in the research period from 2007 to 2021 with projects no. 59778706 and 274995005 starting with basic research and reaching into knowledge transfer phases. Other funding has been supporting mainly the cooperation partners like schools and museums during the development and use of ALS.

ALS has meanwhile reached more than 1.3 million lines of code with a COCOMO estimated value of 5 Million €, hundreds of pages of documentation and tutorials, some hours of video material, and more than 50 publications. The effort for the system development sums up to roughly estimated around 150 person-years.

This report recites partially from the available ALS publications. More details of the system and the studies can be found as referenced. This is expected to be the final technical research report for ALS. As the research project has been closed, eventual future versions of the report may only enrich and enhance this version by more details and additional references.

[1] Learners and teachers in the widest sense of this contribution can be students or teachers in schools and universities, visitors and curators in a museum, users and librarians in collections and archives, or similar or cooperating roles in any educational context. In this article we will sometimes just call them users.

1. Introduction

First, it will be important to discuss some basic foundations for digital teaching and learning environments. The fundamental pedagogical concepts for the ALS environment are contemporary *constructivist theories*, recognizing that learning processes are becoming less dependent on teaching content and more on supporting the self-directed process of learning like for example discussed by Arnold in *Assisted Learning* [4] or by Engeström in *Expansive Learning* [5]. Together with the technological vision of *Pervasive (i.e. Seamless) and Ubiquitous Digital Environments*, as envisioned by Weiser [6], self-driven and creative learning supported by digital systems gains high potential for the future of education [3}. Technological, methodological, and social competencies need to be considered together as they influence the individual development of learners to a high degree. We have to think about a learning culture that favors forms of *self-organized and self-directed learning* using modern medialized extensions of ourselves in the sense of McLuhan's *"Extensions of Man"* [7]. For current post-constructivist methods learning has to be oriented towards supported learning processes in which learners discover, adopt, construct, and deconstruct chunks and structures of relevant knowledge. Even in highly digital and therefore increasingly virtual environments, joint learning, reliable authentic reference to the real world with bodily-physical engagement [8,9] seems to be more important than ever for common grounding and meaning adapted to the cultural localized framing in a more and more virtualized and globalized world. To bring the learners into such a learning environment and keep them growing mentally we need platforms with a low threshold, wide walls, and high ceiling [10] as thematized by Papert and Resnick [11]. This can be expected to become even more important in the next decades [3].

2. Theoretical Foundations

The educational environment ALS has been based on several methodological foundations [10]. In this section we will refer to some of the most important pedagogical theories as well as the resulting systemic model for ALS. More about the evolution, details, and rationales of this approach can be found in [12–15].

2.1 Educational Foundations

Since the end of the 20th century, pedagogical theories and didactic methods increasingly follow constructivist approaches. Arnold discussed *Assisted Learning* as a systemic-constructivist model of self-directed learning [3]. Reich followed a social interactionist-constructivist approach focusing on critical construction, reconstruction, and deconstruction while he outlines: *"In the field of educational theory it draws on diverse approaches that flow from a multimodal, multidimensional and multiparticipant understanding of learning processes"* [16]. In the same sense, most contemporary educational approaches assume that learning is an active construction process, where a learner creates an individual mental representation of the world. However, it has been indicated that this process is not purely subjective, as early radical constructivists like Maturana and Varela hypothesized [17], since each subject is in social relationships within their communities and modalities of action and communication. More than ever, any statement or construction about reality is subject to viability through changes in interests and power as well as social, economic, cultural, symbolic capital formations in the sense of Bourdieu [18].

Learning thus depends strongly on individual prior knowledge as well as on the social, natural, and technical environments, where learning takes place and knowledge can be acquired. Even when we have to question Piaget's rigid step-by-step development model [19] because of the social, societal, and cultural influences of learning, his fundamental conclusion about learning remains groundbreaking, in our words: *It is not possible to transfer knowledge from one person to another person; instead, each person must construct it by him- or herself depending on previous knowledge, skill level, attitudes, and current context.* As a corollary:

Learning is not passive storage, but active construction of knowledge, which has to be reflected and supported by a learning environment through its medialized interfaces.

Closely related to the interactionist-constructivist and the systemic-constructivist approaches is the theory of *Expansive Learning* of Engeström [5]. His theory follows the so-called *cultural-historical theory of activity* [20,21] founded in the 1920s by researchers such as Vygotskij [22] and Leont'ev [23] and further differentiated in the *Critical Psychology for Self-Determined Learning* by Holzkamp (as discussed e.g. by Engeström [5]). According to Critical Psychology, learning in general means the appropriation of an object's meaning by a learning subject and not the adoption or achievement of a normative educational ideal. In addition to concrete things, this also includes abstract and symbolic representations. Thus, Expansive Learning addresses individual or collective learning processes with the goal of exploring possible courses of action, competencies experienced in social relationships and self-determination as a result.

In contemporary constructivist models, the role of a teacher is therefore not to impart knowledge, but to support learners in their individual learning process through a well-balanced measure of instruction by the provision of a resilient scaffold of cultured knowledge about facts and methods. Bringing in technology, the process might be supported further by a responsive medialized knowledge-building environment, which we will call a *Knowledge Media Management System (KMMS),* or more technically, a *Knowledge Media Machine*. Digital media and information systems bring us closer to the idea of constructivist and individual learning than any technology before. They enable people to set up or join social and cultural environments for the negotiation and reflection of common ground. The current challenge that arises in the area of cultural learning in our information-loaded digital world is *authenticity* and *not truth,* other as often currently discussed. It will be increasingly difficult or impossible to track down the sources of information and belief. As the socio-digital processes are so fast, sometimes even called *viral*, that it may be difficult and grueling to decide, what shall be the common ground for education. Even if there would be a stronger bias to scientific foundation, it will be hindered by the complexity through a flood of informational contributions, systemic structures, and discourses. Recent discussions about how to manage a pandemic and related social behavior or about the meaning and validity of content generated by Artificial Intelligence (AI) systems may be signs of the end of old science and the beginning of a new way to manage educationally and even politically scientific contributions, insights, beliefs, and consequences.

The challenge therefore will not only be to teach the concepts of science, but also the genesis as well as the limits of knowledge and common ground in social, political, and cultural processes. These processes are based on the activities of the individual in social roles and cultural settings [20,21]. People need to be taught and supported to become serious, critical, creative but purposeful producers of medialized content in a social dialogue and discourse, instead of being just the consumers of predefined technical and informational constructions [24]. Digital interactive media have the potential for this next step in education to critically reflect and communicate so-called facts, knowledge, and cultural heritage [10]. This turn from *Constructivism* to *Post-Constructivism* or *"New Realism"* – in a positive sense – can be a key for the role of digital media in education. *Knowledge Media* can provide "handles" into the mental and physical creation processes of how knowledge is derived, formed, changed, connected, and used. It helps to actively relate or translate objects of discourse to facts, facts to concepts, concepts to behavior, and behavior to culture. This reflects the genesis of knowledge and, if practiced by learners, gives a deep understanding about the formation and role of knowledge and culture. Such a knowledge-media approach can be seen as a form of post-constructivist teaching and learning, since it follows the constructivist approach of building personal mental models of the world, but goes further in respect to a strong interaction with the real world *("Lebenswirklichkeit")* to prove the knowledge for relevance and resilience.

2.2 Media Models for Ambient Environments

As discussed above, digital learning environments shall be supporting the individual construction of sustainable knowledge, i.e. knowledge that has long-term relevance in real life contexts [9]. Such systems need to support individual and as well cooperative social learning by establishing a strong relationship to the physical environment, to the human bodies of the learners, as well as to their social contexts. In the recent development of multimodal interactive systems we see a revolution in the design of user interfaces like in *Peripheral Media* (e.g. embedding immersive media), *Tangible Media* (e.g. interactive touchable boards and tables), *Mobile Media* (e.g. smartphones and tablets), and *Wearables* (e.g. smartwatches and intelligent fabrics) embedding the learner not only mentally but bodily as well (Fig. 1). This shell model can serve as a basic systemic foundation for post-constructivist learning environments like ALS.

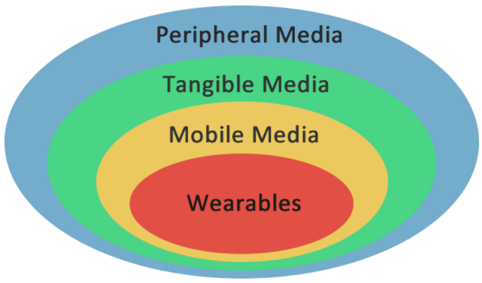

Figure 1. Shell Model of ALS illustrating how learners will be embedded by media technologies [8,9].

From a cognitive perspective this shell structure can be subdivided into segments that can be seen as part of the digital environment or part of the user, in our case the learner (Fig. 2). This illustrates the perception of the users differentiating between him- or herself and the environment.

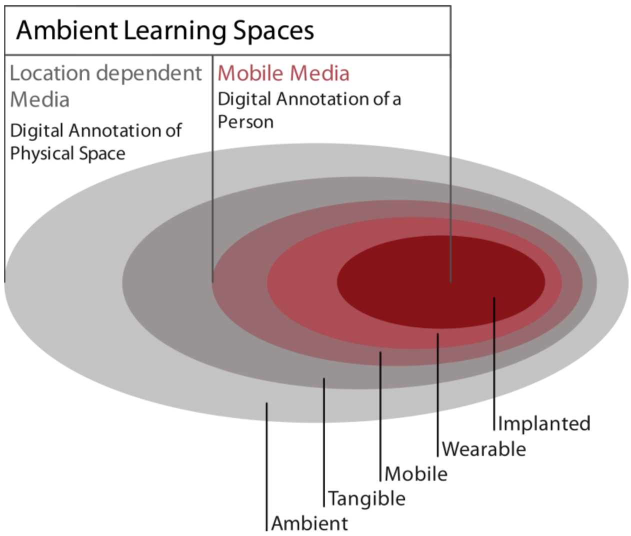

Figure 2. Shell Model of ALS structured into the user and the digital environment [1].

To enable or support the pedagogical concepts discussed above, including the teaching of necessary digital media competencies, we developed over nearly two decades a systemic technological concept for the digital media platform ALS [1,10,15,25] that has been successfully used in a multitude of real world teaching and learning contexts.

In ALS media provided for learning or media created by the learners themselves can be accessed and changed by a variety of modular interactive frontend applications accessing a central backend repository for practically any type of digital media. A multimedia platform for teaching and learning needs to support a wide variety of basic media types like text, 2D and 3D graphics, photos and videos in standard as well as in 360° formats. These basic media will be the building blocks for higher media structures and interaction modalities. Access to the media will be possible through various interaction modalities, like media viewers and editors, browsers and dynamic graphs, augmented, mixed and virtual realities, interactive wearables [26] as well as movement and gesture recognition [27]. The media created by learners or teachers shall be manageable and reusable in different contexts to support the creation of networked knowledge.

The media stored in the environment shall be enriched by semantic annotations from application contexts. The platform shall allow flexible personal, group, and public ownerships based on the roles, social and spatial relationships of usage. Informal annotations will be done by tagging. Other annotations for the media are more formal relationships to higher level concepts like thesauri or taxonomies. Semantic informal or formal markup will transform the media into *Semantic Media* related to real world contexts [28,29]. Tags usually already stem from ad hoc references during social use while some tagging can be done semi-automatically from the context of use itself, like topics of a project or geographical and chronological references throughout the process of use [30].

2.3 Computational Platforms for Teaching and Learning

The process of digitization of teaching and learning over the decades was accompanied by the development of digital platforms supporting certain activities and storing teaching and learning materials [29].

<u>Learning Management Systems (LMS)</u>

In the last 20 years the main type of support platform in the area of computer-supported teaching and learning, have been *Learning Management Systems (LMS)* supporting mainly the following activities:

- user and role management
- course management, including scheduling, tracking and reporting
- storage of course materials together with authorships
- communication and notifications
- discussion groups and forums
- archiving and restoring courses

LMS have a long history. They started to be developed in the 60s of the last century with already large systems like PLATO. With the availability of internet- and cloud-based solutions like WebCT, Blackboard, and Moodle, more flexible and widely available platforms have taken over and allowed the use of LMS through a variety of internet-connected devices like PCs, notebooks, tablets, and smartphones. The basic goal, and at the same time, the main drawback of LMS is their course-centered approach. Learning and teaching is oriented along classes, courses, and schedules. LMS are reflecting this organizational and technical perspective to learning in educational institutions and proposals for their redesign have been made (e.g. [31]).

<u>School Management Systems (SMS)</u>

As more and more digital teaching, learning, and management applications found their way into schools and universities, it showed that identity and role management has to be refined and separated from the LMS and other application platforms. So-called *School Management Systems (SMS)* played this role for the different teaching and learning applications. Another important role of SMS is a "Single Sign-On"-capability that saves the users of several applications to login and logoff from each of the systems separately. Typical functions of SMS are:

- user profiling
- admission management
- management of exams, assessments, grades, and academic progression
- monitoring rewards, scholarships, qualifications, certificates, and graduations
- access rights for content
- authorization for applications
- network access functions
- attendance and activity logs

SMS have been often been based on general user and identity management systems like LDAP and similar systems with only low modeling capability for the special purposes and roles of teaching and learning situations.

<u>Learning Content Management Systems (LCMS)</u>

Learning and teaching is always based on media as the means for communication and external representation. We therefore need *Media Management Systems (MMS)* to support and reflect the contents and didactic methods themselves. Steps in this direction are *Learning Content Management Systems (LCMS)*. LCMS functions comprise mainly the following:

- upload, download, and management of contents (assets)
- support for different media types like documents, presentations, images, videos, 3D objects
- authoring tools for the different media types
- search functionality in storage and archives
- markup for media mainly for search purposes
- Digital Rights Management (DRM)

LMCS have been built in various ways often tightly connected to certain technological solutions, platforms, or operating systems. One special goal was to foster *Reusable Learning Objects (RLO)*.

<u>Knowledge Media Management Systems (KMMS)</u>

LCMS are mainly used to manage media objects (MO) for teaching and learning without explicitly reflecting meaning, knowledge, and context. As MOs are anchor and reference points as well as carriers of knowledge to be acquired, discussed, and enriched, we use the notion *Knowledge Media (KM)* and call such platforms *Knowledge Media Management Systems (KMMS)*. Typical functions for KMMS are additionally to those of LCMS:

- semantic markup to create KM from MOs
- browsing in semantic networks, knowledge-based search functions, and editors
- interactive applications to support teaching and learning with KM
- reasoning with KM and automatic creation of changed or new KM
- versioning and reuse of KM
- distribution and community functions for KM

It showed that ALS will need functionalities of all these platform types [32]. In the following Section 3 the basic architecture of ALS following these requirements will be described. Then in Section 4 applications, the Learning Modules will be shown with examples. Section 5 introduces management and authoring components of ALS. The role of the knowledge representation in ALS will be discussed in Section 6.

3. Architecture for an Educational Environment – ALS Infrastructure and Technologies

Ambient Learning Spaces (ALS) is the name of an integrating infrastructure and a digital *Knowledge Media Machine (KMM)* in the previously described sense, connecting *Frontend Applications (ALS Application Modules)* for mobile, stationary, and immersive interactive computer devices with a shared *Backend System (ALS Repository)* for persistent storage.

3.1 The ALS Architecture

To implement the pervasive experience of an integrated seamless media environment, ALS has been based on a cloud-based backend storage system, the *Network Environment for Multimedia Objects (NEMO)* [2,25,33]. Together with some early learning applications the initial architecture looked like sketched in Figure 3 [1].

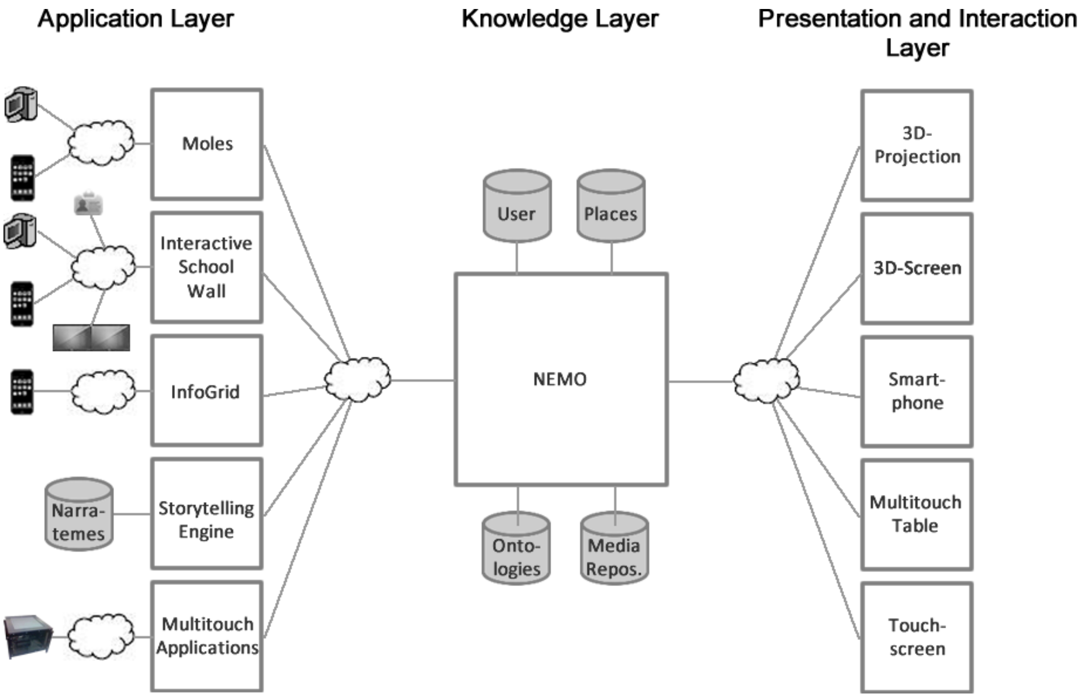

Figure 3. Initial ALS system architecture emphasizing the central storage (knowledge layer) with the applications on the left and the device types on the right.

This basic architecture has been only refined through the evolution of ALS (Fig. 4). Most of the frontend applications including the authoring systems are web-based for a maximum flexibility. *NEMO* can be installed and operated inside or outside institutions, depending on internet web access, bandwidth, ownership [34], and the volume of digital media to be used. The ALS *Portal* combines a *Learning Content Management System (LCMS)* with functionality to annotate, edit, and link media to the corresponding application modules. Various integrated *Content Creation and Editing Tools (Authoring Systems)* can be used inside the environment without any need to install and connect other software systems or to externally manage the media.

Following Weiser's vision [6] of ubiquitous applications using digital devices of different size and capabilities reaching from small mobiles ("Tabs"), through larger mobile displays ("Pads") to large interaction environments ("Boards"), and even larger media domes have been integrated in a pervasive, i.e. seamless way into one interactive media environment [35].

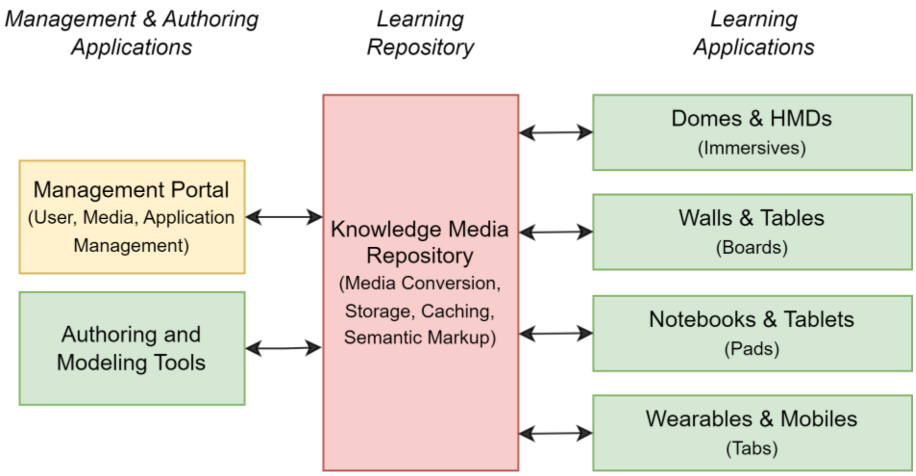

Figure 4. Final ALS system architecture.

3.2 ALS Wearables and Mobiles

As discussed above, authentic education through social activities in real world contexts is a post-constructivist approach to build individual knowledge within cultural settings. Therefore learners, especially school students, need to leave homes and schools to enter live spaces like urban, industrial, and natural environments or places of professional collections like museums and archives to experience authenticity. With networked mobile ALS applications for personal smartphones, tablets, or wearables [35], the KMM can be with the learners in the sense of *"Bring your own Device (BYOD)"* [36]. This enables learners to carry the scaffold of learning in form of interactive applications and prepared knowledge structures with them, study in context, and collect new data and media to be brought back or automatically transmitted to their learning repository.

3.3 ALS Walls and Tables

To visualize larger and more complex information structures, larger displays will be needed. ALS provides applications for large interactive boards (TV touch screens) called *InteractiveWalls (IW)*. Alternatively to the IWs there are *InteractiveTables (IT)* supporting other spatial working setups, like arranging groups standing or sitting around table-like displays. Additionally to an IW, an IT allows the use of *Tangibles (Fiducials),* i.e. physical objects that can be placed on the IT to interact with the applications, like wooden figures for tagging or filtering. Additionally, after searching, discussing, and collecting media with mobiles in physical context, learners need to select and arrange their findings to answer questions or create abstractions of what they found. This can be done in social processes that will typically take place in schools or team spaces with the larger devices.

3.4 ALS Immersives

Immersive media create special perceptions for the learners. However, they are more a result of the human body and mind than of a certain kind of technology. Sherman and Craig distinguish *Physical Immersion* and *Mental Immersion* besides *Immersion (in general)* [37]. We will refer to both, physical and mental immersion, when we discuss immersive media in the context of ALS. The more immersive applications will be available, the more we will create *Mixed or Cross Reality (MR/CR) Learning Environments* [38–41]. Typical immersive situations can be created in ALS using smartphones or tablets for *Augmented Reality (AR)*, Head-Mounted Displays (HMDs), IWs, ITs, or InteractiveDomes (ID) for 360° *Virtual Reality (VR)*. HMDs have been used in the ALS project. We found them to be very attractive to visitors in museums, but not very practical e.g. for hygienic reasons. However, it can be expected that there is an increasing number of owners and users of HMDs in homes using devices like cardboard-smartphone solutions, basic systems like Oculus Go, or higher performance gaming HMDs. This may be an interesting option for the future of learning. ALS is capable of delivering content for such setups in any context.

3.5 API and Application Model Layer of NEMO

The *Application Programming Interface (API)* and the *Application Model Layer* of *NEMO* provide the application information structures needed by the frontend learning applications. This model has been implemented as an object-oriented class structure with APIs for the frontend applications. These applications will usually be connected to certain data structures to access their information models in the backend storage. The basic media created and stored by one application will be accessible by other applications as well.

3.6 Service Layers and Functions of NEMO

NEMO has been implemented as a service-based architecture (Fig. 5).

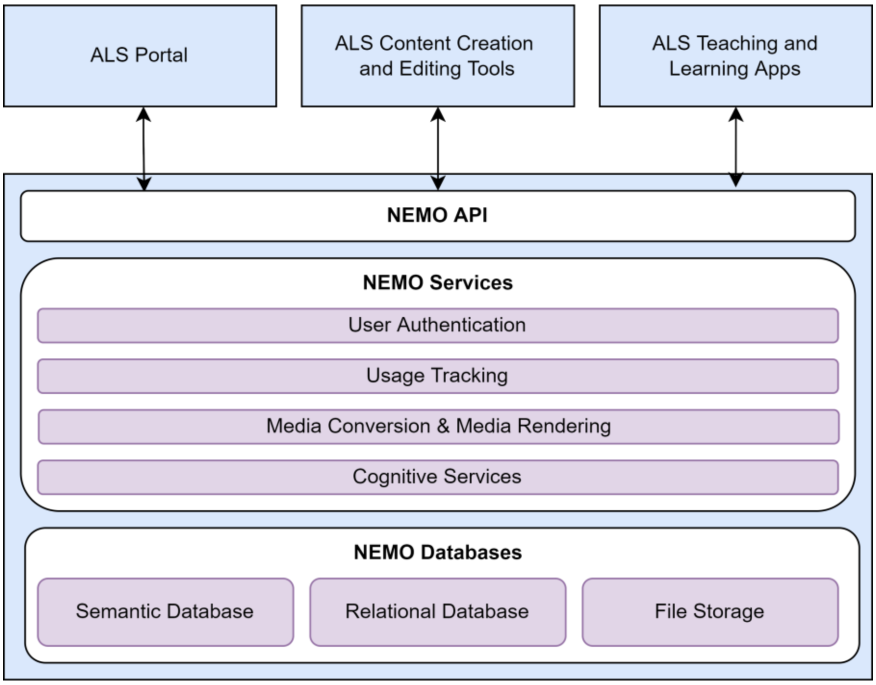

Figure 5. *NEMO* Service Layers [32}.

User Authentication: Administrators can define institutions and assign accounts with different capabilities for them through the ALS *Portal* (Section 5.1) [34]. Teachers, curators, or moderators can create and change accounts for the learners or visitors. They can also define tasks or project groups, if a learning application has been designed for teamwork (e.g. *MoLES*, Section 4.7). Depending on the ALS application, only certain user roles have the capabilities to publish and unpublish information and media created by the learners for public display or reuse. "Public" in ALS can mean that media will be available for other users (e.g. a class or a group) in an ALS environment or accessible through the internet by any user outside of ALS.

Usage Tracking: The *NEMO* framework includes a tracking module that can be used to anonymously log and track user requests from ALS applications. To inspect the tracking data the ALS *Portal* contains a tracking visualization and evaluation module. This gives insights on preferences of content or interaction and about problems encountered. It offers statistics of movements, interactions performed, and media accessed indicating where and how often media files have been requested (Fig. 16). This has been mainly tested for mobile AR applications in museums to see which artefacts have been found with AR overlays displayed (InfoGrid, Section 4.6). This enabled curators to improve their expositions by changing artefacts, media overlays, and spatial settings.

Media Conversion: As digital devices with very different sizes and capabilities are used in ALS, an automatic media converter has been built, which transforms media to the best fitting size, resolution, or aspect ratio to be cached and delivered to the application devices. Additionally, the *NEMO 3D Object Converter (NOC3D)* can be used to automatically create 3D models of physical objects from a series of photographs taken [42,43]. The user can upload photos and videos into the object converter, which then automatically processes the sources using photogrammetric methods building a 3D object with an increasing quality with an increasing number of images taken (Section 5.4).

Cognitive Services: When the ALS *Portal* is used to upload media files into NEMO for any ALS application, it is optional but useful to provide semantic tags. To simplify and speed up the process of tagging, the Cognitive Services analyze the selected media and provide tagging suggestions for the user. The user can accept or reject the suggestions. In experimental settings the Cognitive Services layer used AI methods for semi-automatic tagging. This has been found useful with certain applications to add contextual information to the media.

3.7 Media Storage and Database Layer of NEMO

The central backend storage is implemented by a *Logic and Database Layer* in *NEMO* to provide persistent storage of semantic media. Media created and bound to objects representing the learning discourses define a semantic web. Several media in different formats for different devices can represent an object of the world and make it visible. *NEMO* enables the learners to reuse media created or collected through one frontend application in other applications for related learning contexts and topics.

Semantic Database: NEMO makes use of a Semantic Database to store information in an RDF information model. The SPARQL and LINQ query languages are used to access content in the database.

Relational Database: A relational SQL-database has been used for general application support. After experimenting with semantic databases it showed that they can become quite slow. So for the storage of standard data structures as well as algorithmic search the SQL-database showed much better performance and met most of the requirements.

File Storage: For the storage or large media objects (BLOBs) a standard filesystems is used. The data structures only store references to the BLOBs to keep the other databases small and efficient. It seemed to be helpful for import, export, backup, and similar applications to name the media objects and files in a way that they are human-readable and can be identified more easily through certain media management applications or by administrative users.

In the sense of *Cloud-based Networking, NEMO* can be hosted on basically any physical or virtual machine in a network. It can be viewed as a distributed cloud-based storage system to serve any frontend application meeting the ownership, digital rights, and security requirements. Depending on the size and number of larger media to be copied or streamed through a network to the stationary or mobile applications, the physical locations of the servers need to be optimized. We usually placed one *NEMO* server inside larger institutions like a school or museum besides the provision of several central servers. Therefore it was possible to immediately start with one of our central servers when initiating an ALS project with an institution and later migrate to the local server.

3.8 Connecting ALS Environments

Multimodal ALS learning applications are connected through the common backend repository *NEMO*. Such ALS instances (e.g. in a school or a museum [28]) can be connected to each other through cascading their *NEMO* backends into a higher mesh of ALS environments. If a *NEMO* backend cannot provide some service and content, the request can be routed in a defined order to the *NEMO* backends of other ALS systems connected. This creates a flexible structure of proxies to provide and access local as well as remote content, i.e. common and shared knowledge media spaces (Fig. 6). Each ALS environment with its own *NEMO* backend can be a smaller or larger installation depending on the needs with respect to content, ownership, media size, or network bandwidth.

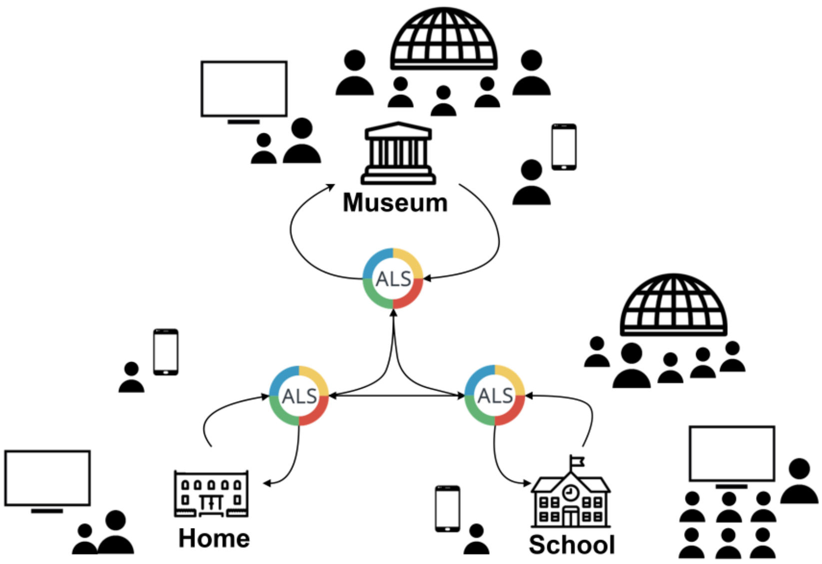

Figure 6. Connected ALS Environments [28].

3.10 ALS Implementation

ALS has been implemented using mainly web technologies. The frontend applications are loosely coupled with the backend server through web-services. The servers have been built using Microsoft IIS (Internet Information Services) with the web-framework ASP.NET, using HTML, CSS, JavaScript, and C# to connect to Chromium-based browsers for the frontend applications.

Smartphone apps have been implemented as browser apps or as a native app based on Unity in the case of the AR system. Meanwhile we would recommend trying browser-based AR frameworks for this to have purely web-based frontends for all applications and devices. For the storage, standard filesystems for large media objects, MySQL-databases for general application support, and BrightStarDB for semantic and logic modeling has been used. Media conversions have been implemented with FFmpeg and caching to optimize space usage and speed. For the AR environment the Unity framework with Vuforia has been used. To implement the photogrammetric functions of creating 3D objects from images and videos we used VisualSFM and CMPMVS in the beginning and AliceVision later, with the latter bringing the best results.

ALS has been built through more than 1.3 million lines of code with a COCOMO[2] estimated value of 5 million €. The effort for the system development has reached about 150 person-years. The ALS system has been developed, tested, used, and improved mainly in operation over more than 10 years in schools, museums, urban spaces, and nature parks.

4. Multimodal Applications for Learning – ALS Frontend Modules

In this section ALS Application Modules will be described that have been implemented, used, and tested in schools, museums, natural habitats, and urban spaces over several years. These interactive and multimodal learning applications have undergone many changes through their practical use and the accompanying pedagogical as well as usability evaluations mostly done in real world contexts. Details about the studies and design changes can be found in the publications referenced in the following descriptions.

4.1 InteractiveWalls and InteractiveTables

A vivid system like ALS with various applications needs integrating and enveloping applications. In ALS this is mainly done with the *InteractiveWall (IW)* [44–46]. The layout of the applications within the IW can be defined by a layout editor.

The IW is also available as the *InteractiveTable (IT)* with additional functions like the recognition of *Fiducials*, i.e. physical objects placed on the table will be recognized in shape and position by the IT. This allows additional physical interaction to learning applications for example for placing, moving, tagging, or filtering information.

IW and IT often served as access systems in public spaces like school foyers (Fig. 7) or entrance areas of museums (Fig. 8). They invite to activate the different applications, browse media, and discover or connect media to meaning.

Figure 7. An InteractiveWall (IW) with four screens in a school foyer (Carl-Jacob-Burckhardt Gymnasium, Lübeck, Germany).

[2] COnstructive COst Model, for a first rough software cost estimation; the calculation for staff and infrastructure has been estimated about twice as high, whereas the direct funding amounts to 1 million euros.

ALS can instantiate any number of *IWs* or *ITs* with different sizes and layouts connected to one *NEMO* backend to create large spatial installations of ambient media. Walls like the *IW* have shown to be an important building block for ambient environments in many different contexts of usage. After many years of usage and evaluation in different educational institutions we can recommend starting an ambient environment with solutions like the *IW*.

4.2 MediaGalleries – Static and Dynamic Knowledge Media Collections

In ALS, *IWs* and *ITs* can provide *MediaGalleries* to display collections of raw as well as selected, grouped, tagged, and categorized media semantically bound to objects of the learning domain. Figure 8 shows the interaction with a *MediaGallery* for a media collection in the Buddenbrookhaus (Heinrich-und-Thomas-Mann-Zentrum).

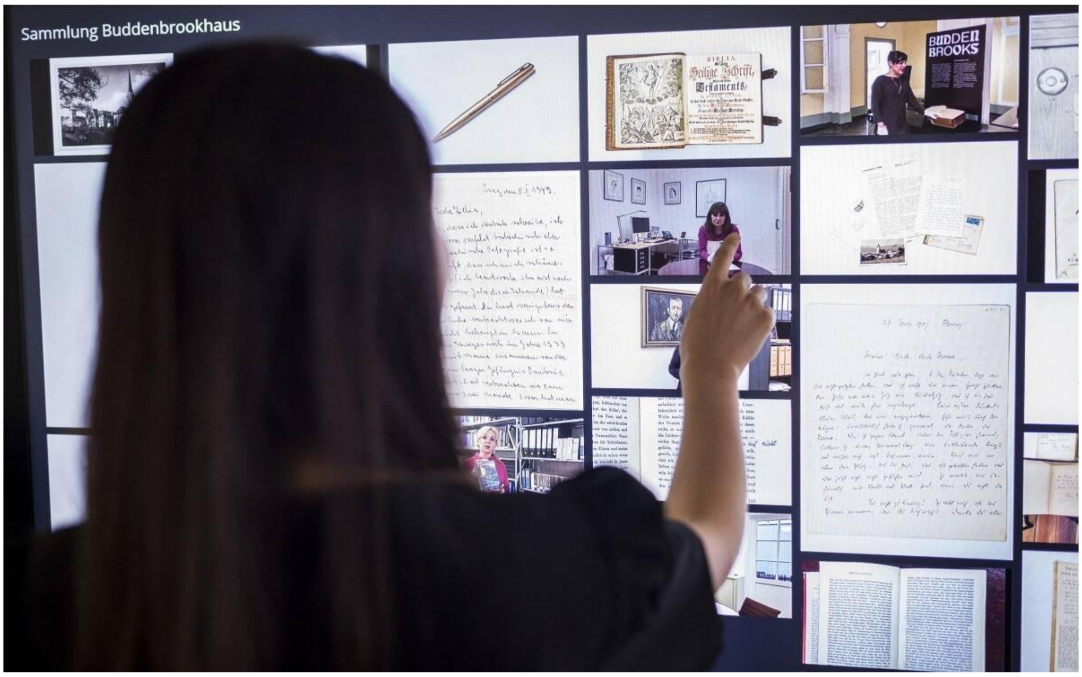

Figure 8. An *InteractiveWall* with MediaGalleries in a museum (Buddenbrookhaus – Heinrich-und--Thomas-Mann-Zentrum, Lübeck, Germany).

A *MediaGallery* may be constructed as a manually selected fixed collection of media. Alternatively it can be the dynamic result of a semantically tagged collection of media, automatically filtered and constructed from a repository. A dynamic *MediaGallery* based on tags is one way of making use of semantic markup connecting and visualizing meaning to media collections.

4.3 TimeLine – Chronological Structures constructing History

The ALS *TimeLine* [30,47] displays an interactive multidimensional time scale visualizing knowledge entities with chronological information and dependencies (Fig. 9 and 10). The entities represent *events* at a point or period of time. Events can be annotated with *semantic tags* and can be assigned to a *category*. Depending on the zoom level, events will be grouped and combined to higher order events. When zooming in, the groups of events dissolve and the individual events become visible. Events can be presented by a set of media of different media types like text, image, audio, and video.

To visualize categories, a *TimeLine* consists of one or more *Sub-TimeLines*, i.e. semantic dimensions over the same period of time. For example, political events can be seen from different perspectives (e.g. "People", "Historical Context", and "Legal Contracts" like in Fig. 9). This provides *multiple perspectives of history* and helps to identify, study, and explain causalities and other dependencies between the events. Learners can hide and display Sub-TimeLines and can thus adapt the whole visualization to their own interests and knowledge. *TimeLine* shows, as a typical constructivist tool, how history can be constructed seen from different perspectives. In the *TimeLine* application, learners can navigate with mouse or natural multi-touch interactions (gestures) deliberately through the chronological graph and explore knowledge entities with annotated and categorized content. When selecting an event, related media (documents, images, audio, video, 3D) will be displayed (Fig. 10). Zooming in and out in time can be done by pinch gestures.

Using the *NEMO* user authentication, curators, teachers, and learners can collaborate physically or virtually to create, edit, and enrich *TimeLines*. Users with sufficient permissions may specify the tags and categories to be assigned to the events. This is particularly useful in school or museum contexts, where teachers or curators define a set of categories that shall be used by learners to study, annotate, and categorize events in a certain sense. During COVID-19, *TimeLine* projects have been created collaboratively and remotely in schools using the sharable cloud-based media space of *NEMO* (Fig. 9).

Figure 9. A *TimeLine* about the European Union constructed collaboratively and remotely by a school class of the Hanseatic School of Business, Economics and Administration in Lübeck.

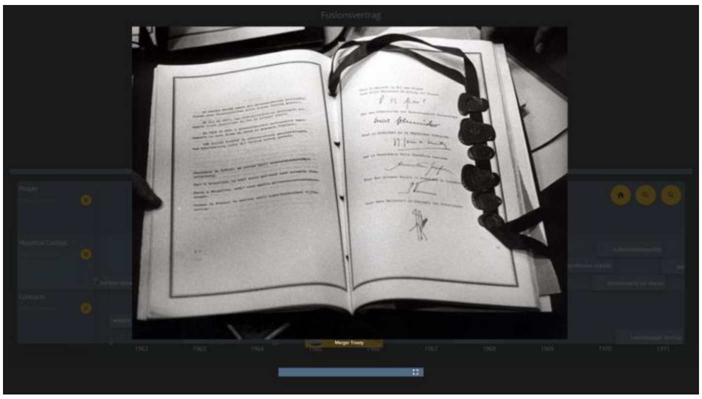

Figure 10. A *TimeLine* showing a detail of an event in one of the sub-TimeLines.

4.4 SemCor – Semantic Networks and Serendipity

SemCor is an ALS learning application for active search and knowledge discovery in a visualized graph structure [29,30] typically shown on *IWs*. It allows interactive exploration of semantic correlations between knowledge media entities to inspect interrelated information in a *semantic web* (Fig. 11). Teachers or curators can provide knowledge entities as starting seeds to explore semantic correlations from there.

Figure 11. A *SemCor* graph visualizing semantic correlations for the seed entity "Thomas Mann" displayed in the center of a dynamic force-directed graph. Nodes of the graph represent related entities, whereas edges between nodes represent semantic relations. This screenshots shows a semantic network in the museum Buddenbrookhaus created from DBpedia and Wikipedia data.

SemCor can be connected to a predefined semantic repository to search for related entities. Once entities have been found, they are grouped into categories and visualized dynamically in a configurable force-directed graph. Entities can be selected to further expand the visualized knowledge space from there. Selecting a knowledge entity, more detailed content will be displayed to be explored further. *SemCor* will search and dynamically deliver new knowledge entities in the graph that can be selected by the learners. These entities are automatically searched and selected through certain search algorithms and filters. *SemCor* visualizes the mesh and complexity of world knowledge and motivates explorations through the *serendipity* phenomenon.

The knowledge repositories for *SemCor* can be self-created or chosen from available ones. The standard system works with DBpedia and Wikipedia. Other external repositories with well defined knowledge domains and semantic relations, like the Europeana for cultural heritage, have been connected to ALS as well.

4.5 HyperVid – Rhizomes of Knowledge for Storytelling

HyperVid is a web-based *hypermedia system* in ALS. It allows linking images and video footage to create a *hypervideo* (Fig. 12). The final hypervideo can be presented on an IW. It can also be integrated in web-pages, e.g. the homepage of institutions. *HyperVid* promotes connected thinking and storytelling. It supports joint learning with narrative time-based multimedia.

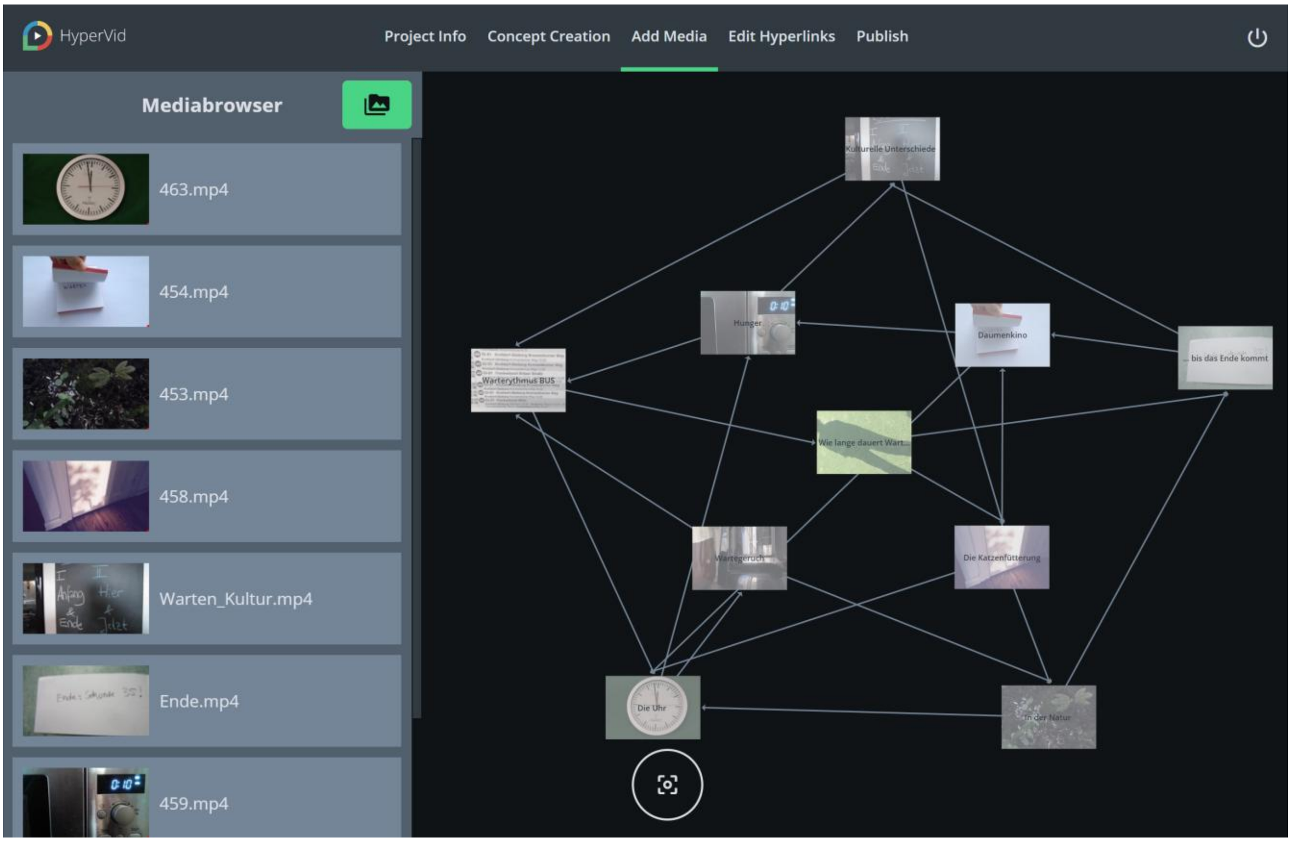

Figure 12. *HyperVid* editor showing the production of a hypervideo consisting of multiple interlinked video fragments. This screenshot shows an art project built in a teacher workshop with elements re-used from the work of an art class to represent cultural aspects of "Waiting".

Additionally to standard image and video formats, *HyperVid* can use 360° images and videos as well to create video-based VR environments (Fig. 13). The connectors will be jumping points in a panoramic scene to switch to other locations. Through this, a virtual video-based 3D space will be created, which can be explored. To prepare images and vid-eos, the embedded authoring systems *ImageEdit* and *VideoEdit* can be used [48] (Chapter 5).

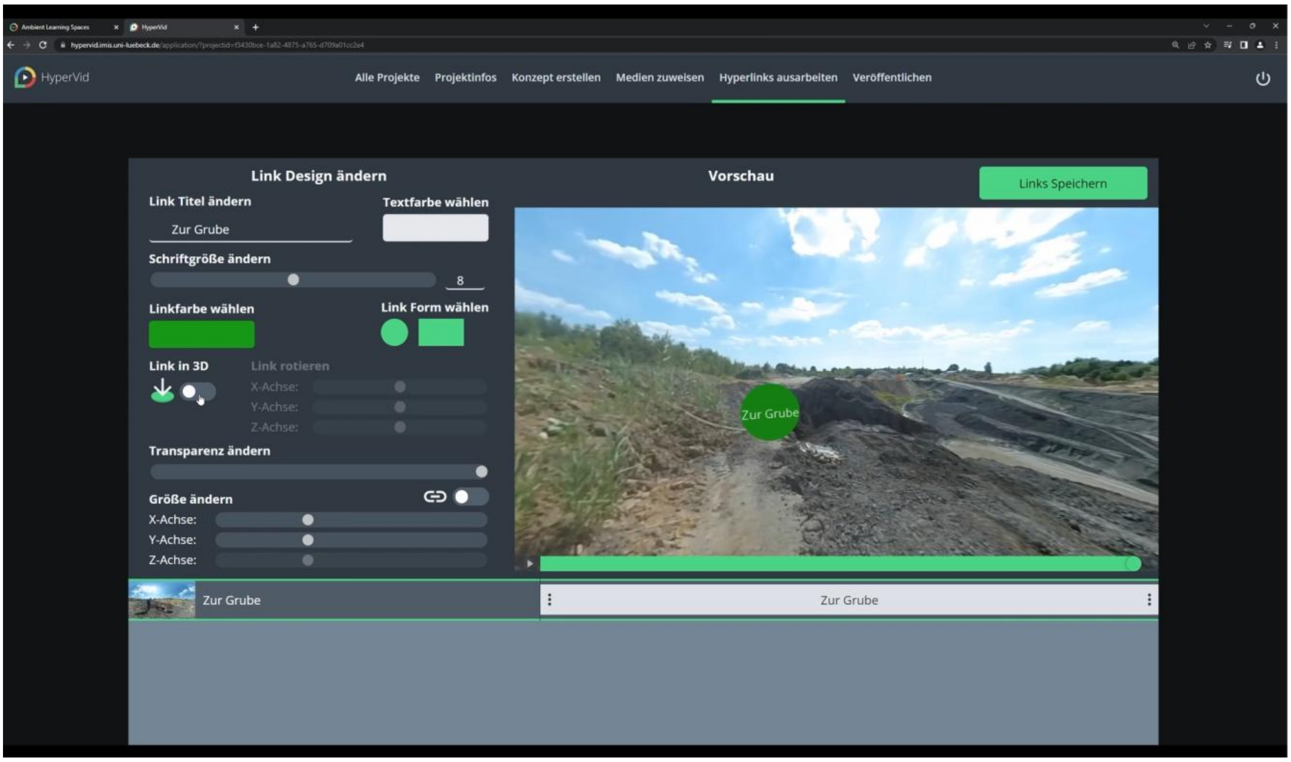

Figure 13. *HyperVid* showing a preview of the construction of a link or jump marker (green circle) within a 360° video to change the location in the 360° scene.

4.6 *InfoGrid – Information Layers through Augmented Reality*

InfoGrid is an *Augmented Reality (AR)* mobile app to explore physical environments by searching for active objects (targets) with digital informational overlays made of images, audio, or video clips as well as static or animated 3D models [36]. The learners direct their smartphone camera towards scenes like displays and artifacts in a museum (Fig. 14 left). Besides delivering images, *InfoGrid* is able to stream audio and video data from the connected *NEMO* repository. Additionally it can display a map or a floor plan to support orientation or to give guidance in complex rooms (Fig. 14 right). *InfoGrid* has not only been used as a turnkey application system, instead learners, like school students, constructed AR tours by themselves [38] and museum curators were able as well to set up their own AR tour [39].

For the production of 3D objects from image and video footage, a converter has been implemented that can be used by teachers, students, and curators to create their own AR tours. For this, photos or videos of physical 3D objects will be taken. A special module of the *NEMO* media conversion layer as well as the *3DEdit* authoring system will be used to create these 3D objects [42,43] (Section 5.4). The *InfoGrid* app contains an inline 3D placement editor for mobiles to place and align overlays into the real scene [49] (Fig. 15).

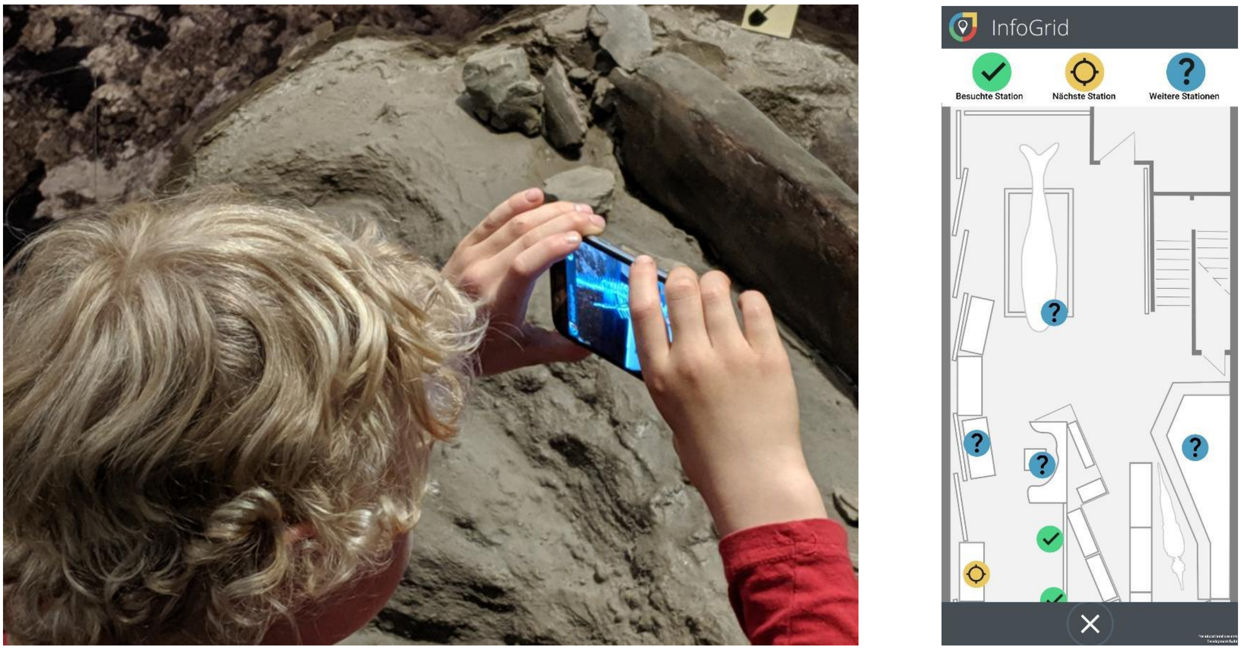

Figure 14. Left: *InfoGrid* displays a 3D whale skeleton and animated body augmented over exhibited paleontological whale bones; Right: floor plan for guidance with visited, new, and recommended next AR targets inside the Museum for Nature and Environment in Lübeck, Germany.

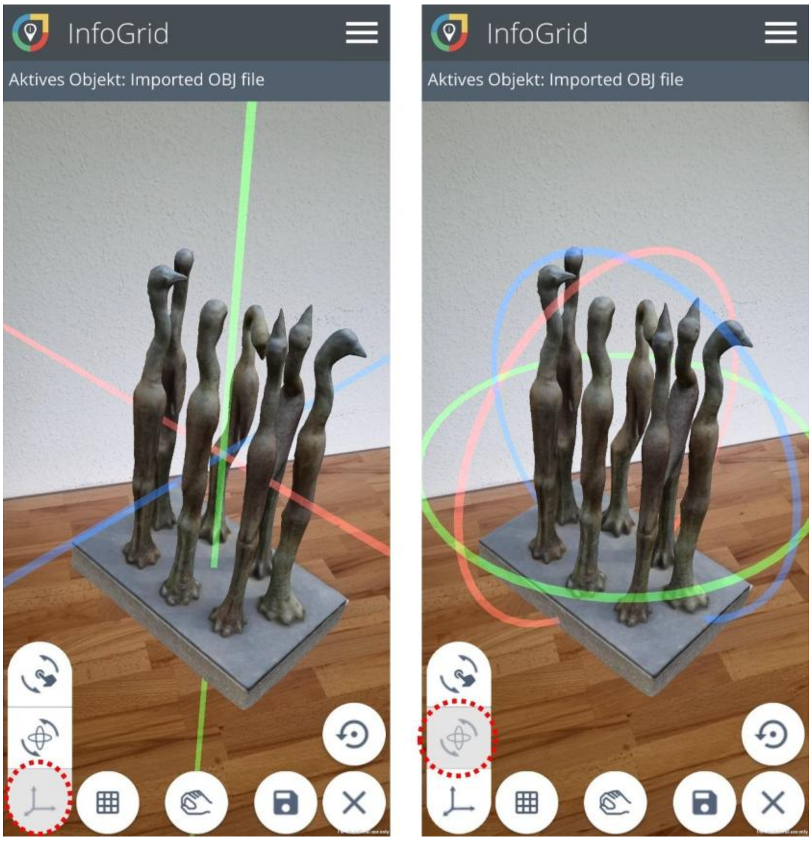

Figure 15. *InfoGrid* 3D object placement editor (showing a 3D-model of "Sieben Vögel" artwork of Günter Grass, Günter Grass-Museum Lübeck Germany).

Several studies evaluated interaction methods to place AR overlays including tracking and logging the interaction layer of the InfoGrid app [49–54] (Fig. 16).

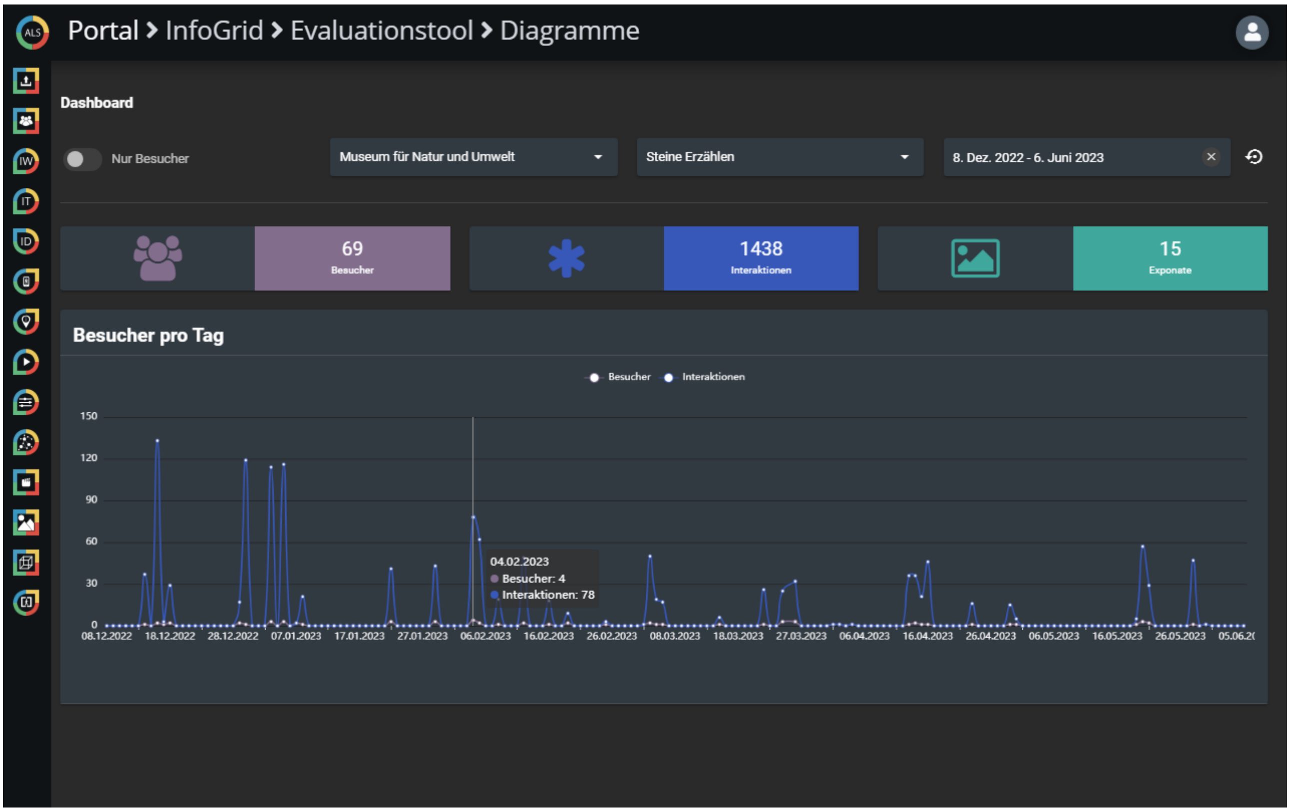

Figure 16. *InfoGrid* evaluation system with statistics about users and interactions.

4.7 MoLES – Going Mobile for Challenges and Search

The *MoLES (Mobile Learning Exploration System)* mobile app provides a task-based teaching framework to guide through a series of tasks and challenges along a topical and geographical learning path ([36], [55–57]). A task in *MoLES* may for example be to take pictures of certain plants or buildings or to capture videos of industrial processes. Learners have to answer questions, do research, note data and findings, and collect tagged media about the objects and contexts and follow the next task until the whole tour has been completed. In schools the learners typically will go out in small groups of two to four with fewer mobile devices than group members to be forced to discuss and decide together, what shall be noted and collected (Fig. 17). *MoLES* will transmit collected data and media automatically as soon as possible via internet connectivity to the *NEMO* repository. The knowledge media content collected will then be available for presentations or other purposes during lessons and can be used in further learning projects.

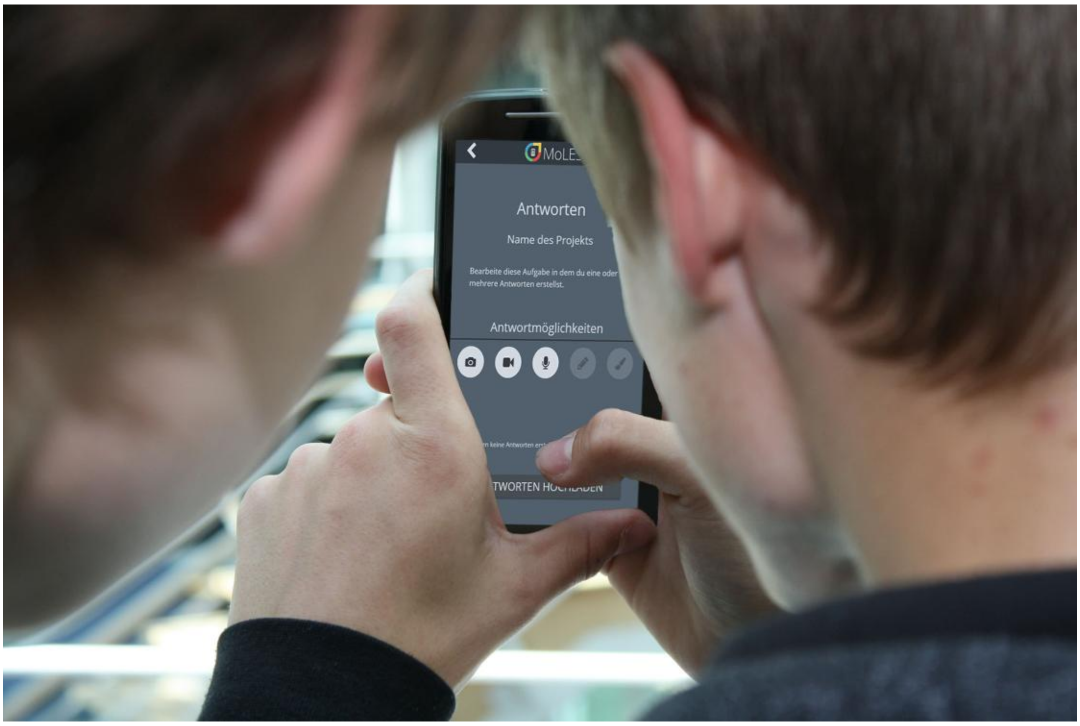

Figure 17. Two school students solve tasks with *MoLES* while following a tour during a project about modern architecture. The data, images, or videos collected will be uploaded to *NEMO* for later use.

4.8 InteractiveDome and HMDs – The Experience of Immersion

The media currently in use for immersive ALS applications are mainly 360° images and videos. Both can be enriched by interactive elements, like in *HyperVid*, to create non-linear 360° hypervideo structures with interactive buttons (jump markers) to change the location leading to another image or video (Section 4.5).

As experimental presentation and interaction technologies, we used VR HMDs (Head-Mounted Displays) like Oculus Rift and Oculus Go as well as the ALS *InteractiveDome (ID)* as a form of a peripheral (spatially embedding) device. Rectangular 360° images and videos can be transformed into polar HMD and dome formats to create strong immersive experiences. The *ID* system in one of our partner schools offers space for up to 15 persons (Fig. 18) [35].

Another technology for immersive presentation and interaction are Web VR solutions that can be integrated in the *IW, IT,* and the *ID.* VR engines, like in the Unity framework, can create similar effects. The VR modes additionally support the interaction with 3D objects that can be created by teachers, learners, and curators themselves through a photogrammetric pipeline from images and video footage [42,43] (Section 5.4).

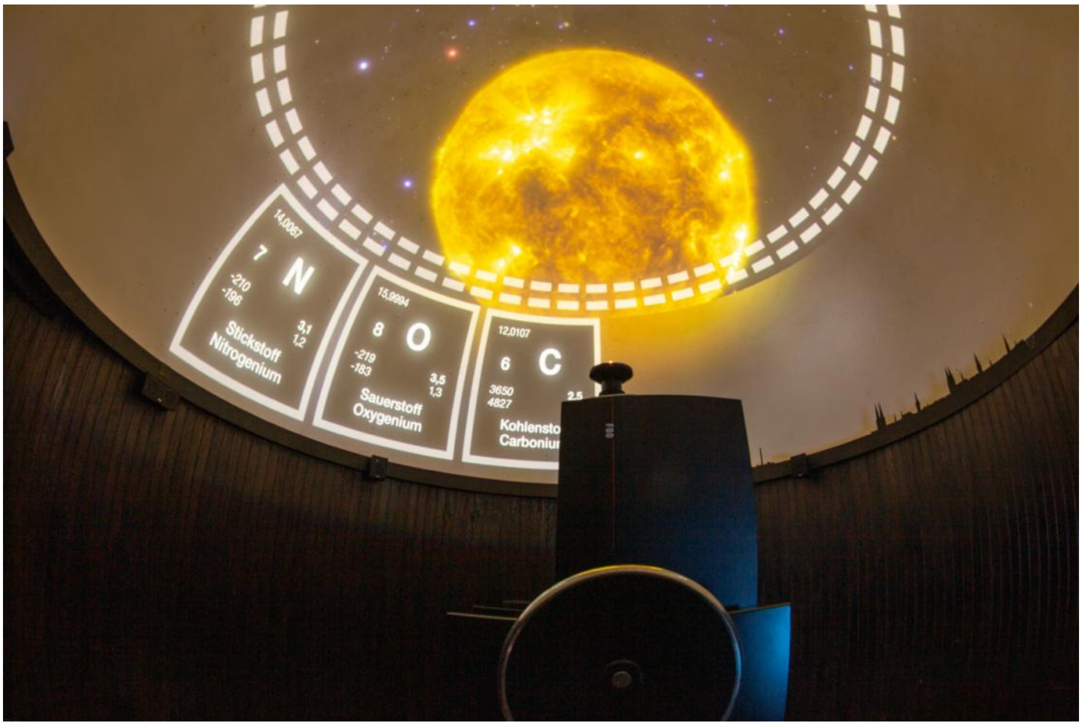

Figure 18. 360° productions can be brought into the ALS *InteractiveDome* system. The photo shows the historical school planetarium "Sternkammer" of the Grund- und Gemeinschaftsschule St. Jürgen in Lübeck, Germany, which has been refitted with a digital projector combined with the history planetarium projector and connected to ALS (© photo courtesy of Ralph Heinsohn).

5. Media Management and Authoring for Learning – ALS Portal and Editors

For a dynamic learner-centered and self-driven learning process it is a basic requirement that learners and teachers themselves need to be capable of creating and annotating media as well as managing the learning platform by defining new users or by activating or deactivating application modules for certain users or the whole platform. In ALS this resulted in a management module we called the ALS *Portal* used for all ALS Modules. Additionally, the need to create, edit, and manage media resulted in several easy to use integrated *Authoring Applications* for images, video, and 3D objects.

5.1 Portal

The ALS *Portal* is a kind of *Learning Content Management System (LCMS)* (Section 2.3) to create and edit information and media for all ALS learning applications and to activate or deactivate these applications. Users can access the *Portal* through a standard web browser. After logging into the *Portal* it presents a list of ALS applications that are available for a user account (Fig. 19). The user can then create or edit information and semantic markup. Media can be up- and downloaded to and from ALS. All data and media entered through the *Portal* will be stored inside *NEMO*.

To make it easier to use ALS, the need for embedded authoring tools has shown to be important. This saves the users, as well as the schools or museums, from buying, installing, maintaining such tools and connecting them to their learning environment. In museums the staff started to work with images and videos themselves instead of placing expensive orders to external media companies changing the relationship to the artefacts of their museum.

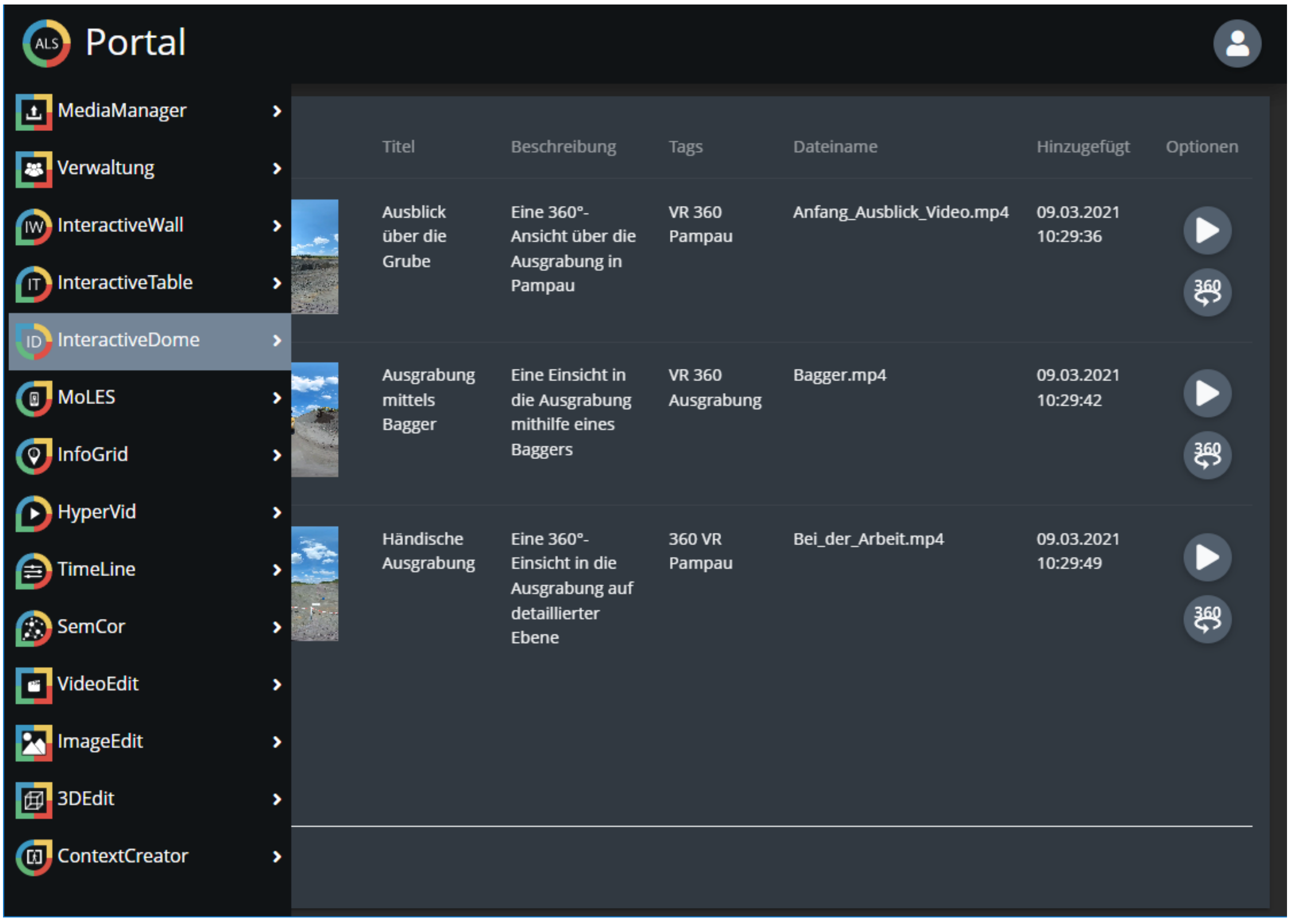

Figure 19. ALS *Portal* for the management of the ALS applications and content. In this case the user selected the available 360° dome media for the paleontological excavation site Pampau.

5.2 ImageEdit

We implemented an image editor to create and change 2D images like photos taken and graphical products designed. *ImageEdit* is purely browser-based (Fig. 20) and can be used from the *Portal*. The editing functions have been reduced to the basic needs, so that the use of the editor can be learned within few minutes.

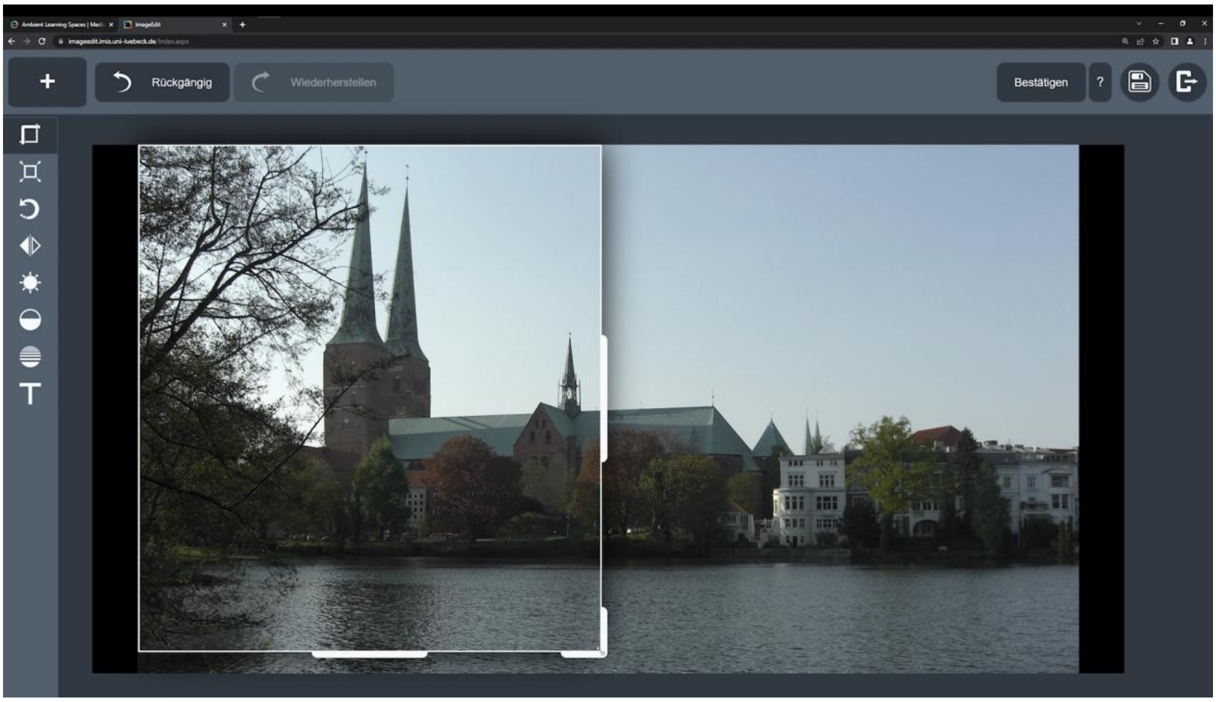

Figure 20. *ImageEdit* screen with an image being manipulated.

5.3 VideoEdit

Similar to ImageEdit, *VideoEdit* is web-based authoring tool that can be used to create and edit video footage [48] (Fig. 21). Users can upload their media files such as images and videos either from their mobile phones or through a local computer into *VideoEdit* and the *Portal*. These media files can then be merged into a new video file. *VideoEdit* supports adding a separate audio track as well as a text overlay track and has important additional functions such as adapting the volume of the resulting video. After preparing the video, *NEMO* renders the video using the FFmpeg framework. The resulting mp4-file is automatically made available for all ALS applications through the *Portal*.

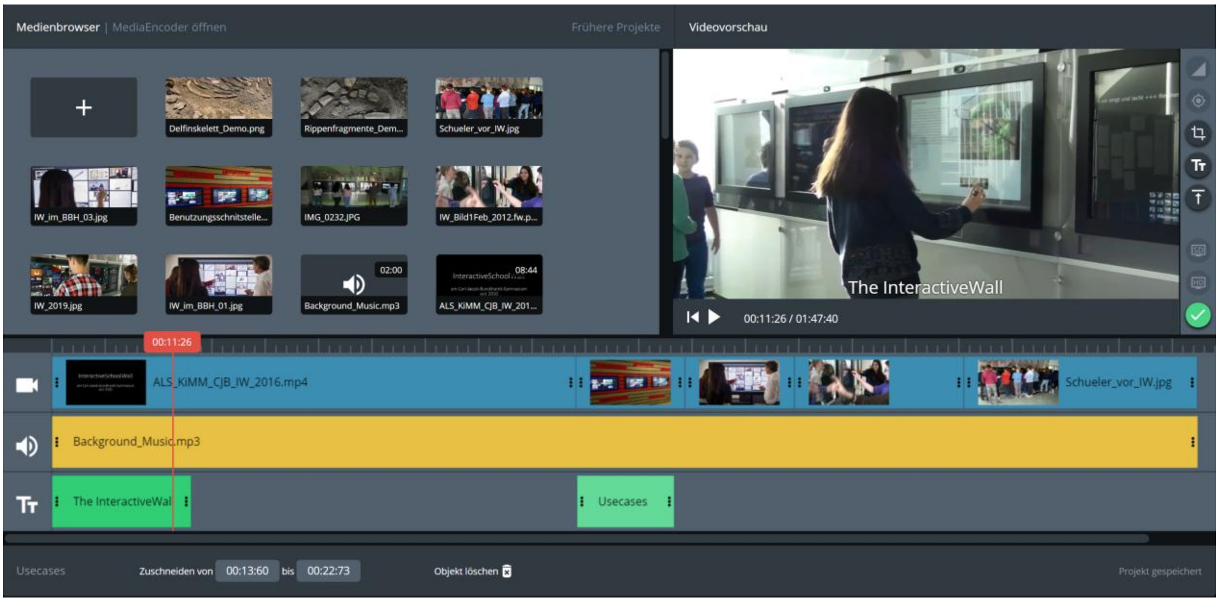

Figure 21. *VideoEdit* screen with a video being created from different sources.

5.4 3DEdit

We implemented a special functionality for the production of 3D objects from 2D photographic footage [42,43]. This has especially been used to generate 3D models for augmented or virtual reality applications. After creating a new 3D object using the ALS *3D Object Converter NOC3D* or alternative tools the resulting objects usually contain unwanted artefacts and are randomly placed in space (Fig. 22 left). *3DEdit* can then be used to cut and delete the unwanted artefacts from the 3D object and to align its position, scale, and orientation in space. After finishing this process (Fig. 22 right), the 3D objects can be used in ALS applications such as the *MediaGallery* or *InfoGrid*. However, it showed in our experiments, that creating well rendered 3D objects needs more practice and knowledge than creating images or videos. Usually the learners, teachers, and curators needed assistance by 3D experts. This problem may be overcome by more easy to use photogrammetric tools and automatic sizing and placement in 3D space.

Figure 22. Raw 3D model after automatic photogrammetric rendering (left) being clipped and transformed with *3DEdit* to final a 3D model (right).

5.5 Narrator

With the ALS *Narrator* module inside the *Portal* it is possible to create storylines for ALS applications [58]. The user can define and annotate story elements with semantic information in a way that the *NEMO* framework can create relations between the elements. This has been tested within *InfoGrid* to create storylines guiding the users in AR enriched exhibits (Section 4.6 and Fig. 14 right). The Narrator can guide the users depending on their interests, earlier visits, or topics of interest along a path of activities. The dramaturgical structure can be based on some historic models for storylines like models from the antique or contemporary ones. First results showed that the knowledge models can support the creation of storylines. More experiments will be needed to evaluate how well such knowledge-based guidance will be perceived by users like visitors in museums.

5.6 Profiling and Personalization

All media stored in *NEMO* using the *Portal* can be semantically annotated during the creation and uploading process. Besides topical areas, the annotation can also include information about the language used within the applications and media or the recommended age of the target audience. Using the profiling and personalization service ALS applications liked described above for a *Narrator* in *InfoGrid* can use the appropriate data about the user to behave in a more user-centered and therefore more expected way.

6. Knowledge Representation for Learning – ALS as a Knowledge Media Machine

As already discussed above, the formal and explicit representation of knowledge can play an important role for interactive multimedia learning applications. Such combinations of knowledge and media have been called *Knowledge Media (KM)* [59] and the process of KM modeling *Knowledge Media Design (KMD)* [60]. *Knowledge Media Management Systems (KMMS)* combine media management AI methods. KM and connected interactive applications can be structured like shown in Figure 23 [29]. In this model KM consist of *Knowledge Entities (KE)* with one or more *Media Objects (MO)* attached to them. This KM can then be accessed reusable through interactive *Knowledge Applications (KA)*. ALS has many properties of a KMMS in this sense [28–30].

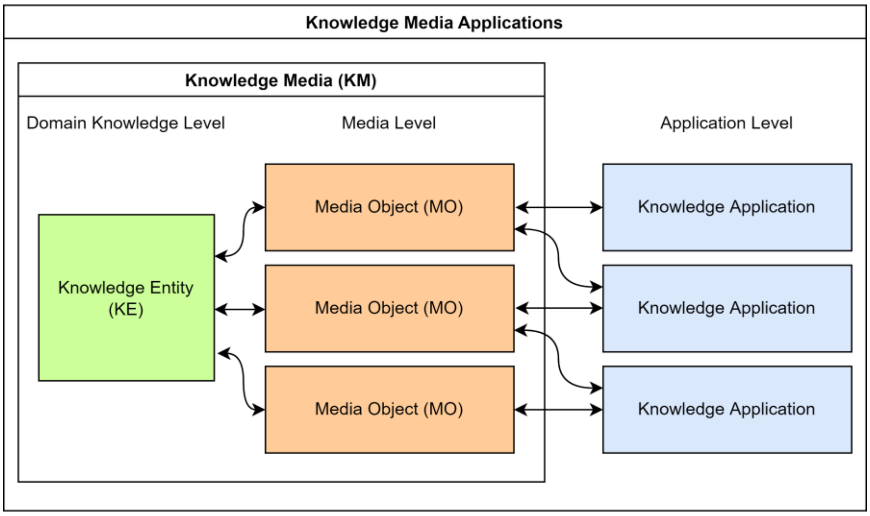

Figure 23. Knowledge Entity (KE) with several Media Objects (MO) accessed through interactive Knowledge Applications (KA).

6.1 Semantic Modeling

The construction of a KM from plain MOs or vice versa can be done through *Semantic Modeling*. There are semantic modeling (markup) methods with different strengths and weaknesses to define KM and higher KM structures:

Tagging is a method of associating meaningful *terms* to MOs. Tagging is meanwhile widely used in the area of social media networks. Even while being a simple method, it already supports search, clustering, classification, and many other useful semantic methods.

Thesauri can be seen as catalogs of predefined meaningful tags with references to *synonyms* and *antonyms*. The use of controlled thesauri can lead to well-defined knowledge structures, like widely and successfully applied in professional collections of museums, archives, and literature.

Classification is used to create explicit abstraction hierarchies, called *classes and inheritance structures* with *subclasses* and *superclasses*. This creates a strong form of type sensitivity and is an efficient way of defining attributes and methods when building refinement structures.

Semantic Networks are relational networks for associative knowledge structures, where KEs are usually connected (associated) unidirectional to other KEs.

World Concepts are a way of defining and delimiting knowledge domains. A set of KEs defines and delimits a domain for certain application and reasoning contexts. This can be helpful for systems like *TimeLine* or *SemCor* (Sections 4.3 and 4.4).

All of these methods are well known and have been applied successfully in the area of symbolic artificial intelligence (AI), especially when constructing *Knowledge-based Systems (KBS)* and *Expert Systems (XPS)* through formal knowledge representation. Many of these systems spent some of their modeling capabilities and resources to support explanations for learning and understanding their reasoning methods and outcomes. It is only natural to extend the discussion about computer-supported knowledge, media, and learning with the future role and perception of new interactive technologies [61].

6.2 Browsing, Searching, and Editing generic Knowledge Structures

Large or complex knowledge structures need to be inspected to grasp and understand their meaning. A typical generic method is browsing KM through textual or graphic displays. Besides the structural properties, the content of the KM will be accessed by displaying associated MOs like in *SemCor* (Section 4.4). Besides browsing, the semantic markup will help to find certain entities through search methods. Using methods like approximate search or pattern-matching, heuristic search processes can be implemented.

6.3 Interactive Knowledge Applications

As already outlined, knowledge browsers, search methods, and content editors are generic knowledge applications. When it comes to didactics in certain teaching situations, more specific interactive knowledge applications need to be tailored to content-specific visualizations and functions using context-dependant interaction devices. An example is *TimeLine*, which has been specialized to chronological knowledge structures along the dimensions of different information categories (Section 4.3).

6.4 Reasoning with Knowledge Entities

If there are knowledge-based inference models for KEs, reasoning on KM can be applied. Typical reasoning techniques will be *production systems* (rule-based), *constraints* (formal dependencies), or general *logic- and frame-based reasoning* (inferences like classification, induction, deduction, abduction). This also allows (semi-)automatic classification and creation of new KM from of existing ones. We experimented in *MoLES* (Section 4.7) with semi-automatic tagging algorithms proposing tags dependant on the current context, task, and learner. Especially the automatic tagging with places, time, and topics showed to be meaningful.

6.5 Versioning and Reuse of Knowledge Media

It will be helpful, in larger educational organizations even necessary to develop KM for different users in different versions. This supports *reuse* across several learning applications to save effort and allow connectivity through content between knowledge applications and domains. ALS in its current form needs available KM to be copied for new purposes. This has the advantage of making it easier for the learners to keep track of their personal KM, but has the disadvantage of managing copies and the need for additional space especially for larger MOs like videos or 3D objects. Thus *versioning* may be a helpful additional method for individual and context-specific knowledge construction.

6.6 Distribution and Community Functions

In many cases communities of users are creating and managing semantic worlds collaboratively. Therefore KM need to be available in distributed data clouds. Data-driven modeling and inference can be used for the communication between KMMS and users to notify about new or changed KM. These are typical functions of current social platforms. This will be useful in educational and community building contexts as well. In ALS we used different ALS instances for new application worlds like for different museums with their special content. At the time being, we did not incorporate classical social platform communication functions like notifications, chat, or mail messages that might be helpful for team-based learning. However, typically ALS will be connected to *Learning Management Systems (LMS)* in place to connect to the curriculum and practice of teaching.

7. Summary and Conclusions

Based on constructivist and post-constructivist models of pedagogy the learning environment *Ambient Learning Spaces (ALS)* has been designed and implemented to study self-driven learning in connected authentic environments. ALS provides the shared backend repository *Network Environment for Multimedia Learning (NEMO)* that connects to modular interactive frontend *Learning Applications*. These multimodal learning applications are running on a range of digital interaction devices like *wearables, mobiles, tangibles,* and *immersive media* to support all typical learning contexts. Modalities and media types used comprise *text, 2D and 3D graphics, standard and 360° video, augmented and virtual reality.* The various frontend applications can reuse and share media for different learning purposes providing *"wide walls"* for teaching and learning.

The media stored in ALS can be enriched to *Knowledge Media* by *Semantic Modeling* to support medialization of certain topical areas and linking of chunks of medialized knowledge. ALS provides integrated *Authoring Tools* to create and edit images, videos, 3D objects. *Hypermedia* for *Digital Storytelling* and *Virtual Environments* can be constructed by creating links and semantic markup between the media. With ALS we have shown that interactive learning with Knowledge Media enables learners to critically reflect, deconstruct, and thoroughly reconstruct their knowledge in *authentic environments like urban spaces, natural habitats, industrial areas, or historic sites.* This can be seen as a foundation for a *"high ceiling"* in teaching and learning to build, reflect and change complex social and individual knowledge structures in a fast changing world.

ALS has been implemented, piloted, and studied for many years in real world contexts in daily use. Pedagogical and ergonomic studies accompanying the entire development period have continuously examined the qualities and effects of ALS and allowed to redesign and optimize the environment for different learning contexts. As a result, ALS has achieved high levels of usability and educational qualities to ensure *"low thresholds"* of usage after introductory support.

ALS can be seen a systemic blueprint for future educational *Knowledge Media Management Systems* or *Knowledge Media Machines* for teaching and learning allowing to connect different educational environments and contexts like schools, museums, urban spaces, nature parks to connect to social and cultural knowledge while developing individual knowledge.

ALS has been built as more than 1.3 million lines of code with a COCOMO estimated value of more than 5 Million €, hundreds of pages of documentation and tutorials, many hours of video material, and more than 50 publication. The effort for the system development has reached 150 person-years. The ALS system has been developed over more than 15 years together with schools and museums and well as in urban heritage spaces, nature parks and corporate environments.

Acknowledgments

We developed and evaluated the ALS system in the research projects "Ambient Learning Spaces" funded 2007–2021 by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) with projects no. 59778706 and 274995005. We thank our school and museum project partners for their continuous support to do our field research collaboratively in and with their institutions. I like to thank all the contributors to design, build, test, and improve ALS over the years.

References

1. Winkler, T.; Scharf, F.; Hahn, C.; Herczeg, M. Ambient Learning Spaces. In Méndez-Vilas, A. (Ed.) Education in a Technological World: Communicating Current and Emerging Research and Technological Efforts. Badajoz, Spain: Formatex Research Center, 2011; pp. 56–67.
2. Feldner, B.; Günther, S.; Schmitt, F.; Winkler, T.; Herczeg, M. A Dolphin Is a Dolphin Is a Dolphin? Multimedia Enriched Learning Objects in NEMO. In Proceedings of the 9th IEEE Intl. Conf. on Advanced Learning Technologies (ICALT 2009). IEEE, 2009; pp. 29–31.
3. Herczeg, M. The Role of Digital Technologies and Human-Computer Interaction for the Future of Education. In Koch, M. (Ed.), i-com: Vol. 23, No. 2. Berlin/Boston: De Gruyter, 1-9.
4. Arnold, R. Assisted Learning: A Workbook, Landau: Bildungstransfer, 2011.
5. Engeström, Y. Learning by Expanding, Cambridge: Cambridge University Press, 2014.
6. Weiser, M. The Computer for the Twenty-First Century, Scientific American, 1991, 9; pp. 94–104.
7. McLuhan, M. Understanding Media: The Extensions of Man, New York: McGraw-Hill, 1964.
8. Winkler, T.; Reimann, D.; Herczeg, M.; Höpel, I. Creating digital augmented multisensual learning spaces - Transdisciplinary school education between aesthetic creating and building concepts in computer science. In Szwillus, G.; Ziegler, J. (Eds.), Mensch & Computer 2003, Stuttgart: Teubner, 2003; pp. 307–316.
9. Winkler, T.; Reimann, D.; Herczeg, M.; Höpel, I. Learning in our increasing digital World by connecting it to bodily Experience, dealing with Identity, and Systemic Thinking. In Proceedings of SITE 2004. AACE, 2004; pp. 3794–3801.
10. Herczeg, M. Ambient Learning Environments – Multimodal Interactive Teaching and Learning Environments with Low Threshold, wide Walls, and High Ceiling. In Proc. of iCERi 2023, IATED, 2023; pp. 8250-8260.
11. Resnick, M. Designing for Wide Walls, https://mres.medium.com/designing-for-wide-walls-323bdb4e7277 (accessed 08/16/2023), initially published in Design.blog, August, 2016.
12. Herczeg, M.; Ohlei, A.; Schumacher, T.; Winkler, T. Ambient Learning Spaces: Systemic Learning in Physical-Digital Interactive Spaces. In Algorithmic and Aesthetic Literacy: Emerging Transdisciplinary Explorations for the Digital Age. Leverkusen: Verlag Barbara Budrich, 2021; pp. 97-115.
13. Herczeg, M. Education in the Digital Age: A Driving Force or a Lost Place. i-com, Journal of Interactive Media, 20(3), Berlin/Boston: De Gruyter, 2021; pp. 263–277.
14. Herczeg, M.; Ohlei, A.; Schumacher, T.; Winkler, T. Ambient Learning Spaces: Systemic Learning in Physical-Digital Interactive Spaces. In Algorithmic and Aesthetic Literacy: Emerging Transdisciplinary Explorations for the Digital Age. Leverkusen: Verlag Barbara Budrich, 2021; pp. 97–115.
15. Herczeg, M.; Winkler, T.; Ohlei, A. Ambient Learning Spaces for School Education. In Proceedings of iCERi 2019, IATED, 2019; pp. 5116–5125.
16. Reich, K. Interactive Constructivism in Education, Education and Culture, 2007, 23(1); pp. 7–26.
17. Maturana, H.; Varela, F. The Tree of Knowledge. The Biological Roots of Human Understanding, Boston: Shambhala Publications, 1992.
18. Bourdieu, P. Language and Symbolic Power, Boston: Harvard University Press, 1991.
19. Piaget, J. The Role of Action in the Development of Thinking, In Knowledge and Development, Springer, 1977; pp. 17–42.
20. Cole, M.; Engeström; Y. Vasquez, O. Mind, Culture and Activity. Cambridge: Cambridge University Press, 1997.
21. Cole, M.; Engeström, Y. (1993). A cultural-historical approach to distributed cognition. In Salomon, G. (Ed.) Distributed Cognitions: Psychological and educational considerations. Cambridge: Cambridge University Press; pp. 1–45.
22. Vygotskij, L.S. Thought and Language, Cambridge: MIT Press, 2012.
23. Leont'ev, A.N. Activity, Consciousness, and Personality, Englewood Cliffs: Prentice Hall, 1978.
24. Postman, N. The End of Education. New York: Vintage Books, Random House, 1996.
25. Herczeg, M.; Ohlei, A.; Schumacher, T. Ambient Learning Spaces: A Connecting Link between Digital Technologies and Computer-Supported Pedagogy. In Proceedings of INTED 2021, IATED, 2021; pp. 6011–6021.
26. Winkler, T.; Ide, M.; Herczeg, M. Teaching Teachers to Teach with Body and Space related Technologies: Programmable Clothing in Performative Teaching Processes. In Maddux, C.D.; Gibson, B.D. (Eds.). Research Highlights in Technology and Teacher Education, AACE, 2010; pp. 221–228.
27. Ide, M.; Winkler, T.; Bouck-Standen, D. ActeMotion as a Content-Oriented Learning Application in Secondary School: Media Control through Gesture Recognition as a Performative Process in Art Teaching. In EdMedia 2017, AACE, 2017; pp. 1327–1335.
28. Herczeg, M. Ambient Learning Spaces: Chances and Challenges of Interactive Knowledge Media Platforms for Schools and Museums. In Proceedings of iCERi 2022, IATED, 2022; pp. 2378–2388.
29. Herczeg, M. Ambient Learning Spaces: The Role of Distributed Knowledge Media Management Systems for Computer-Supported Teaching and Learning. In Proceedings of INTED 2023, IATED, 2023; pp. 820–830.
30. Herczeg, M.; Schumacher, T.; Ohlei, A. Ambient Learning Spaces: Discover, Explore and Understand Semantic Correlations. In Proceedings of iCERi 2020, IATED, 2020; pp. 7990–7999.

31. Molinari, A. Learning Management Systems: Is it Time for a new Generation? In Proceedings of iCERi 2022, pp. 2122–2130, IATED, 2022.
32. Herczeg, M., Ohlei, A., Schumacher, T. Ambient Learning Spaces: A Connecting Link between Digital Technologies and Computer-Supported Pedagogy. In Proceedings of INTED 2021. IATED, 2021; pp. 6011-6021.
33. Lob, S.; Cassens, J.; Herczeg, M.; Stoddart, J. NEMO - The Network Environment for Multimedia Objects. In Proceedings of the First Intl. Conf. on Intelligent Interactive Technologies and Multimedia (IITM 2010), ACM, 2010; pp. 245–249.
34. Bouck-Standen, D.; Eggert, C.; Ohlei, A.; Herczeg, M. A User Rights Concept for Semantic Media in Ambient Learning Spaces. In Proceedings of CENTRIC 2018, IARIA, 2018; pp. 24–25.
35. Herczeg, M.; Ohlei, A.; Schumacher, T.; Willer, L. Context and Size Matters: Integrated Ambient Learning Spaces from Mobile to Immersive Media. In Proceedings of iCERi 2021, IATED, 2021; pp. 3945–3955.
36. Herczeg, M.; Ohlei, A.; Schumacher, T. Ambient Learning Spaces: BYOD, Explore and Solve in Physical Contexts. Proceedings of iCERi 2020. IATED, 2020; pp. 7979–7989.
37. Sherman, W.R.; Craig, A.B. Understanding Virtual Reality, Morgan Kaufmann, 2003.
38. Winkler, T.; Ohlei, A.; Ide, M.; Herczeg, M. Creating Augmented Realities in the Context of Lessons in Secondary Schools. In Proceedings of EdMedia + Innovate Learning 2019, AACE, 2019; pp. 230–247.
39. Ohlei, A.; Bouck-Standen, D.; Winkler, T.; Herczeg, M. InfoGrid: An Approach for Curators to Digitally Enrich their Exhibitions. In Mensch und Computer 2018 Workshops, Workshop on Virtual and Augmented Reality in Everyday Context (VARECo), Gesellschaft für Informatik, 2018; pp. 345–352.
40. Herczeg, M. Mixed Reality Learning. In Seel, N.M. (Ed.) Encyclopedia of the Sciences of Learning. Boston, MA: Springer, 2012; pp. 2284–2287.
41. Rogers, Y.; Scaife, M.; Gabrielli, S.; Smith, H.; Harries, E. A Conceptual Framework for Mixed Reality Environments: Designing Novel Learning Activities for Young Children. Presence, 11(6), 2002; pp. 677–686.
42. Bouck-Standen, D.; Ohlei, A.; Höffler, S.; Daibert, V.; Winkler, T.; Herczeg, M. Reconstruction and Web-based Editing of 3D Objects from Photo and Video Footage for Ambient Learning Spaces. Intl. Journal on Advances in Intelligent Systems, 11(1/2), 2018; pp. 91–104.
43. Bouck-Standen, D.; Ohlei, A.; Daibert, V.; Winkler, T.; Herczeg, M.: NEMO Converter 3D: reconstruction of 3D objects from photo and video footage for ambient learning spaces. In Proceedings of AMBIENT 2017; The Seventh Intl. Conf. on Ambient Computing, Applications, Services and Technologies, IARIA, 2017; pp. 6–12.
44. Winkler, T.; Ide, M.; Herczeg, M. InteractiveSchoolWall: A Digital Enriched Learning Environment for Systemic-Constructive Informal Learning Processes. In Maddux, C.D.; Gibson, D. (Eds.) Research Highlights in Technology and Teacher Education. AACE, 2012; pp. 117–126.
45. Winkler, T.; Ide, M.; Hahn, C.; Herczeg, M. InteractiveSchoolWall: A Digitally Enriched Learning Environment for Systemic-Constructive Informal Learning Processes at School. In Proceedings of EdMedia 2014. AACE, 2014; pp. 2527–2537.
46. Winkler, T.; Bouck-Standen, D.; Ide, M.; Ohlei, A.; Herczeg, M. InteractiveWall 3.1 - Formal and Non-Formal Learning at School with Web-3.0-based Technology in Front of Large Multi-touch Screens. In Proceedings of EdMedia 2017, AACE, 2017; pp. 1317–1326.
47. Herczeg, M.; Ohlei, A.; Reins, T.; Schumacher, T. Ambient Learning Spaces: Constructing TimeLines through Distributed Collaborative Learning. In Proceedings of iCERi 2021, IATED, 2021; pp. 3972–3981.
48. Ohlei, A.; Schumacher, T.; Herczeg, M. An easy-to-use web-based Video Creation Tool for the Classroom. In Proceedings of INTED 2021. IATED, 2021; pp. 6076–6085.
49. Ohlei, A.; Bundt, L.; Bouck-Standen, D.; Herczeg, M. Optimization of 3D Object Placement in Augmented Reality Settings in Museum Contexts. In Proceedings of the Augmented Reality, Virtual Reality, and Computer Graphics 6th Intl. Conf. AVR 2019, Part II, 2019; pp. 208–220.
50. Ohlei, A.; Winkler, T.; Wessel D.; Herczeg, M. Evaluation of Direct Manipulation Methods in Augmented Reality Environments using Google Glass. In IEEE Intl. Symposium on Mixed and Augmented Reality, ISMAR-Adjunct 2018, Munich, 2018; pp. 266–269.
51. Ohlei, A.; Bouck-Standen, D.; Winkler, T.; Herczeg, M. InfoGrid: Acceptance and Usability of Augmented Reality for Mobiles in Real Museum Context. In Mensch und Computer 2018 Workshops, Workshop on Virtual and Augmented Reality in Everyday Context (VARECo), Gesellschaft für Informatik, 2018; pp. 339–344.
52. Ohlei, A.; Wessel D.; Herczeg, M. Usability of Direct Manipulation Interaction Methods for Augmented Reality Environments using Smartphones and Smartglasses. In Salento AVR 2019; pp. 84–98.
53. Ohlei, A.; Schumacher, T; Herczeg, M. An Augmented Reality Tour Creator for Museums with Dynamic Asset Collections. In Augmented Reality, Virtual Reality, and Computer Graphics, 7th Intl. Conf. LNCS/LNIP Vol. 12243, Springer, 2020, pp. 15–31.
54. Ohlei, A.; Schumacher, T.; Herczeg, M. An Analytics System for the Evaluation of Interactions of Museum Visitors in Augmented Reality Tours. In Mensch und Computer 2020 Workshops, Bonn: Gesellschaft für Informatik, 2020.

55. Günther, S.; Winkler, T.; Herczeg, M. Mobile Learning with Moles: A Case Study for Enriching Cognitive Learning by Collaborative Learning in Real World Contexts. In Proceedings of EdMedia 2008. AACE, 2008; pp. 374–380.
56. Winkler, T.; Günther, S.; Herczeg, M. MoLES: Mobile Learning Exploration System. In Proceedings of SITE 2009. AACE, 2009; pp. 3230–3234.
57. Winkler, T.; Herczeg, M. The Mobile Learning Exploration System (MoLES) in Semantically Modeled Ambient Learning Spaces. In IDC '13 Proceedings of the 12th Intl. Conf. on Interaction Design and Children. ACM, 2013; pp. 348–351.
58. Bouck-Standen, D.; Ohlei, A.; Winkler, T.; Herczeg, M. Narrative Semantic Media for Contextual Individualization of Ambient Learning Spaces. In Proceedings of CENTRIC 2018, IARIA, 2018; pp. 26–31.
59. de Matros Müller, F.; de Souza, M.V. The Role of Knowledge Media in Network Education, Intl. Journal for Innovation Education and Research, Vol. 8, No. 7, 2020; pp. 76–93.
60. Eibl, M.; Reiterer, H.; Stephan, P.F.; Thissen F. (Eds.) Knowledge Media Design. 2005, München, Wien: Oldenbourg.
61. Herczeg, M. The Smart, the Intelligent and the Wise: Roles and Values of Interactive Technologies. In Proceedings of the First Intl. Conf. on Intelligent Interactive Technologies and Multimedia (IITM 2010), ACM, 2010; pp. 17–26.