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Assessing the efficacy of online-only learning versus blended learning in oral radiology courses — a comparative longitudinal study in undergraduate dental students

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For my parents.

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Zusammenfassung

Blended Learning Konzepte werden als eine effektive Maßnahme zur Verbesserung der Kompetenzen von Studierenden betrachtet. Im Zahnmedizinstudium eignet sich die zahnärztliche Radiologie besonders gut, um *Blended Learning* Konzepte erfolgreich umzusetzen, wie eine frühere Pilotstudie an der Heinrich-Heine-Universität Düsseldorf gezeigt hat. Aufgrund der COVID-19-Pandemie waren europäische Universitäten gezwungen, die persönlichen Kontakte zwischen Lernenden und Lehrenden einzuschränken. Präsenzunterricht wurde in eine reine Online-Umgebung verlagert. Ziel der vorliegenden Studie war es, die Effektivität eines *Blended Learning* Konzeptes (Prä-Pandemie) und eines reinen Online-Lernkonzeptes (Pandemie) in der zahnärztlichen Radiologie zu vergleichen.

Zu diesem Zweck wurden zu Beginn und Ende jedes Semesters, in jeweils drei aufeinander folgenden Kursen (C1, C2 und C3), standardisierte Prüfungen durchgeführt. In den drei Prä-Pandemiekursen (Okt. 2018 bis Feb. 2020) wurde ein präsenzbasiertes *Blended Learning* Konzept mit Präsenzvorlesungen in Kombination mit einer digitalen Röntgenbildplattform umgesetzt. Zusätzliche videobasierte Lernmodule wurden in den drei Pandemiesemestern (April 2020 bis Juli 2021) eingeführt. Für die statistische Analyse wurde ein Vergleich innerhalb der Semester mittels gepaarter und zwischen den Semestern mittels ungepaarten t-Tests unter Verwendung des Softwareprogramms R durchgeführt.

Sowohl vor als auch während der Pandemie zeigte sich jeweils ein signifikanter semesterbezogener Wissenszuwachs. Das Wissensniveau in den Abschlussprüfungen in den prä-pandemischen verglichen mit den pandemischen Semestern unterschied sich hingegen nicht signifikant. Auf Kursebene erzielten Studierende, die während der Pandemie die meisten Lernmodule nutzen konnten (C3), signifikant höhere Werte im Wissenszuwachs und den Abschlussprüfungen als Studierende, die diese in nur geringerem Umfang nutzen konnten (Kurse 1 und 2).

Die vorliegende Studie lässt schlussfolgern, dass der pandemiebedingte Rückgriff auf gut konzipierte online Inhalte in Kursen der zahnärztlichen Radiologie einen vergleichbar hohen Wissenszuwachs erbrachte wie das präsenzbasierte *Blended Learning* Konzept vor der Pandemie. Pandemiebedingte psychologische Faktoren konnten in dieser Studie nicht berücksichtigt werden.

Summary

Blended learning concepts are considered an effective method to enhance student skills in higher education. In dental education, oral radiology is especially suited to implement blended learning concepts, as demonstrated in a previous pilot study at Heinrich Heine University in Düsseldorf. Due to the COVID-19 pandemic, European universities were forced to reduce personal contact and shift from face-to-face teaching to an online-only learning environment. The present study aimed to compare the effectiveness of a blended learning concept (pre-pandemic) and an online-only learning concept (pandemic) in undergraduate oral radiology courses.

Standardised exams were held at the beginning and end of each semester within three subsequent courses (C1, C2, and C3). In pre-pandemic courses from October 2018 to February 2020, a conventional blended learning concept with face-to-face lectures combined with an oral radiology platform was implemented. Additional video-based e-learning modules (VBLMs) were introduced during the pandemic semesters from April 2020 to July 2021 (2 VBLMs for C1, 4 VBLMs for C2, and 6 VBLMs for C3). For the statistical analysis, a within-semester comparison was performed by means of paired t-tests and between semesters with unpaired t-tests using the software programme R.

Results show significant knowledge gain in both pre-pandemic and pandemic semesters, whereas no significant differences were found among the results of final exams. Students who received the highest number of additional VBLMs during the pandemic (C3) scored significantly higher in both knowledge gain and final exams compared to students who received a small number of VBLMs (C1 and 2).

The present study provides further evidence that well-thought online-only teaching in oral radiology can be as effective as face-to-face blended learning concepts. As for the limitations of this study, it was not possible to evaluate COVID-19-associated detrimental psychological effects.

Abbreviations

ADEE	Association for Dental Education in Europe
AMEE	International Association For Medical Education
COVID-19	Coronavirus disease 2019
CSLC	Computer-supported collaborative learning
D-learning	Digital learning
E-learning	Electronic learning
F2F learning	Face-to-face learning
HHU	Heinrich Heine University Düsseldorf
ILIAS	Integrated learning, information, and work cooperation system (*German: Integriertes Lern-, Informations- und Arbeitskooperations-System*)
LMS	Learning management system
M-learning	Mobile learning
PBL	Problem-based learning
POL	Patient-oriented learning
SODOTO	See one, do one, teach one
tDCS	Transcranial direct current stimulation
VBLMs	Video-based e-learning modules
ZEFS	Zoom exhaustion and fatigue scale

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1 Introduction

How do we learn? — A short introduction to learning and memory from a cognitive perspective

When considering topics such as online learning environments or blended learning concepts, it is essential first to discuss general principles of human learning and memory processes. Fortunately, there is extensive scientific literature on these topics (e.g., [1]). Several insights from this literature are immediately relevant to my work, especially as they relate to models of learning and memory. Specifically, in models of learning and memory, two fundamental distinctions have emerged. Firstly, memories can be either explicit, meaning that the learner is aware of and able to verbalise knowledge (e.g., Paris is the capital of France [2]), or implicit, meaning that the learner has no awareness of the information and that it is challenging to verbalise it (e.g., how to ride a bicycle or how to drill a tooth [3]). Secondly, memories can be categorised into episodic memories, that is, memories for specific autobiographical events (e.g., what I ate yesterday morning), and semantic memories, that is, memories for facts or general knowledge about the world (e.g., caries is terrible [4]). It is important to stress that semantic memory ("I know") is generally strengthened by repetition, in contrast to episodic memory ("I remember"), which can be weakened by exposure to similar events.

When it comes to forming new memories, also known as "learning" or "encoding", there are three basic principles that govern how successfully memories are stored [1]. First, merely being repeatedly exposed to information does not guarantee to learn it. For example, people have difficulty remembering details of their national currency, though handling money daily [5]. Secondly, memories are better stored if the information to be learned relates to previous knowledge (e.g., [6]). This also has clear implications for studying: For example, remembering facts presented in a lecture will be far easier after completing assigned readings beforehand. Finally, deeper information processing at encoding leads to a higher likelihood of remembering the information later (this is the so-called *levels-of-processing effect* [7]). The level of processing positively correlates with brain activation in corresponding areas [8] and dictates the need for teachers to engage students in multimodal learning techniques, some of which will be discussed later in this dissertation. These principles can guide us in the development of blended/online learning platforms since all of these principles can be applied to different forms of learning.

What about *retrieving* information from memory? One general rule is that knowledge is better retrieved when study and test conditions match, also called *constructive alignment*. This means that preparation for an exam should involve processing the material similar to how it is tested on the exam [9]. Furthermore, memory content retrieval becomes easier with more cues available. Obviously, free recall of facts is more demanding than cued recall, which in turn is more demanding than recognition. For designing exams, this means that teachers have to compensate for the fact that multiple-choice tests (based on recognition memory only) are generally easier to perform than open-answer tests by, e.g., including choices that can be easily mistaken for the correct answer. As a last principle of memory retrieval, the struggle or failure to remember can enhance memory. This implies that the mere act of taking a (difficult) test can improve later memory for the knowledge tested (for review, see [10]). This is called the *test-enhanced learning effect* [11].

1.1 Types of learning concepts

In previous literature, the term e-learning (i.e., electronic learning) has often been defined and used inconsistently. This makes it difficult to identify one single, overarching definition of e-learning. In their systematic review, Basak and colleagues [12] strived to develop a common definition for the concepts e-learning, m-learning (i.e., mobile learning), and d-learning (i.e., digital learning), which will be further introduced in the following paragraphs. Interestingly, they also provided recommendations for teachers, educators, students, and staff regarding the implementation of e-learning content.

1.1.1 E-learning

The term e-learning refers to all forms of learning supported by the use of electronic or digital media [12], for the presentation and distribution of learning materials, and/or to support interpersonal communication. The main feature is the use of the internet [13]. E-learning is also often used synonymously for online learning, telelearning, multimedia learning, computer-supported learning, computer-based training, open and distance learning, and computer-supported collaborative learning (CSCL). In the “e-Learning in Medical Education” AMEE guide by Ellaway and Masters [13], it is summarised as *“the educational uses of technology”*. It includes the simple distribution of digital documents and describes a pedagogical approach that aims to be flexible, motivating, and student-centred. This, in consequence, should enhance interaction, collaboration, and communication [13].

The advantages of e-learning are permanent accessibility and availability of information independent of time and place, ease of updating already existing content, personalised instructions, automated feedback, and data availability. In addition, interactive features, for example, possibilities of control and intervention, allow for a student-centred and student-controlled environment in which students choose the content, learning sequence, learning velocity, time, and media, enabling them to customise an individual learning experience [14].

Three e-learning principles are particularly noteworthy: multimediality, multicodality, and multimodality. First, multimediality describes the numerous options for online content distribution, including various media such as books, video players, audio players, computers, audiobooks, e-books, and e-lectures. Second, multicodality comprises various codes through which the learner is able to receive the information, e.g., (animated) images, texts, hypertexts (with cross-references), animations, simulations, or videos. Third, multimodality is the reception of information through various (primarily auditory and/or visual) sensory modes [15]. In higher education, it is used as a term for receiving information and learning skills through not only different sensory modalities [16] but also through different technologies [17]. Anastopoulou [18] defined multimodality as an *“employment of multiple modalities, interaction styles, and […] interactive devices”*.

Broadening the learning options not only results in increased interactivity but also in higher learning motivation. Therefore, effectiveness (i.e., learning of relevant contents) and efficiency (i.e., learning in a systematic, well-planned, and time-saving manner) of the learning process might be enhanced [14], and knowledge may shift from theoretical to more practical applications. However, disadvantages — such as lack of resources, technical issues, no stable internet connection, and personal isolation, possibly leading to frustration of the learner — are also highlighted in the literature [14, 19-21].

Educators should always consider in advance whether the use of technology is appropriate for the intended purpose. In other words, digitalisation should not exist for the sake of it but should always have specific goals in the scope of application. Until now, digital educational technologies (e.g., e-learning) have been successfully implemented in many aspects of medical [13, 14, 22, 23] and dental education [20, 24-26] from teaching basic anatomy [27], dental terminology [20, 21] to surgical skills [28]. Specifically, the implementation of e-learning in oral radiology courses is thought to enhance diagnostic skills [25, 29-32].

With regard to the structure and design of e-learning, a distinction is made between e-learning with a focus on the content (i.e., for *"accessing materials"*; focus on *"content management such as content upload/download"*) and e-learning with a focus on the process (i.e., for *"participating in activities"*; focus on *"scheduling, discussion, and tracking activity"*) [13]. The conceptualisation and development of e-learning content are associated with high costs for personnel and digital infrastructure (hard- and software). Furthermore, production is time-consuming. However, investing in complex e-learning development tools might not be required since easy-to-use software tools are already available and beneficial for students' knowledge gain and learning efficiency [33].

1.1.2 M-learning

Mobile learning (m-learning) is defined as a specific form of e-learning [34], *"using mobile devices and wireless transmission"* [35]. M-learning holds many new prospects for working with learners in novel contexts [13]. In 2003, Hoppe et al. [35] saw promising potential in this fast-evolving technology. In their guest editorial "Wireless and Mobile Technologies in Education" in the Journal of Computer Assisted Learning, they foresaw that there might be more sophisticated intentions to implement m-learning besides the apparent content delivery.

One of the essential advantages of m-learning might be enabling more active and collaborative forms of learning, especially as mobile devices do not interfere with interaction the way laptops and computers do [35]. Also, m-learning might *“set the focus more on interpersonal relations and on the task at hand”* [35]. Over the last two decades, with the development of technically more sophisticated mobile devices with increasing screen sizes, better accessibility, and availability of online formats, and the accelerating optimisation of e-learning development platforms, the disadvantages associated with the use of mobile devices (e.g., non-optimal screen sizes or incompatible interactions) are gradually diminishing in importance [36].

Studies have already evaluated the readiness of medical [36] and dental students [37-39] for using mobile devices in their learning process and their attitudes toward the educational use of mobile phones. Many authors reported positive feedback and recognised m-learning as a promising opportunity to target students’ individual needs. However, Klímová [40] concluded in her literature review that implementing m-learning in medical education is efficient for acquiring knowledge and skills but only as a compliment to a traditional face-to-face (F2F) course. Since then, many studies have been published investigating the implementation of innovative m-learning in medical education. For example, in 2017/18, Golenhof et al. [27] successfully implemented an *eMedApp* to enhance factual knowledge gain in their undergraduate anatomy course. In 2018/19, Golshah et al. [41] compared two groups (F2F vs m-learning) of 4th-year dental students in identifying cephalometric landmarks and found a lower error rate for the m-learning group. In 2019, Bock et al. [42] developed a mobile application for their pre-existing *PantoDict* oral radiology platform and tested it in a quasi-experimental trial with undergraduate dental students. Results demonstrated that students using the application performed significantly better in the final exam than students in the control group.

1.1.3 D-learning

Digital learning is a broad term for any form of learning facilitated by technology or instructional practices that employ technology effectively. It occurs in all learning domains and disciplines [12]. Despite the uncommon use of the term, d-learning is increasingly used as a substitute for e-learning. D-learning technologies are intended to facilitate and support the learner's understanding of complex contexts and practical applicability to everyday problems and situations.

The definition of d-learning should be distinct from the concept of distance learning. Distance learning describes the contrast to on-site campus education and comprises any remote and online learning [43]. The term digital learning is often used synonymously with e-learning and online learning. For simplicity, I will use the term e-learning to refer to any digital learning concept.

1.1.4 Blended learning

Blended learning combines F2F learning and synchronous (i.e., time-fixed live) or asynchronous (i.e., on-demand, independent of a specific time) e-learning. Blended learning extends traditional learning methods by introducing, integrating, and adding online environments, such as learning management platforms (LMS), learning games, and mobile technologies [44]. Bridging the old with the new approaches showed promising and positive effects for educators and students [46-50] and appeared to increase the effectiveness of modern teaching and learning [44]. It may also define a combination of different instructional modalities and methods. However, as instructional modalities and methods are very broad and define an overly wide range of different learning systems, it is advisable and useful to limit the definition of blended learning to the combination of F2F learning and either synchronous or asynchronous e-learning [45], which will also be the definition that is used throughout this dissertation.

Since digitalisation progresses and students demand an increasingly flexible and remote learning environment, Heilporn et al. [46] broadened the definition of blended learning as a specific form of e-learning, namely a combination of synchronous and asynchronous online learning content. They proposed that all traditional learning settings are shifted into an online environment. In addition, the authors addressed the outstanding issue of how to optimise student engagement in blended online courses through educators’ instructional strategies and investigated the effects between several disciplines in higher education [47]. For this purpose, they first recommend a clear and unified course structure with a sustained course pace. For example, the authors suggest activating course modules with a time difference over the duration of a semester. As a side-effect, this ought to help manage the learner's cognitive load. Moreover, Heilporn et al. [46] emphasised that educators need to assess the relevance of learning material beforehand, consider the choices in topics, activities, and/or resources, as well as make it available through active and interactive learning. To facilitate this constructive alignment, educators need institutional support and, consequently, a *"reliable and robust infrastructure"* [44] as a prerequisite.

For example, online logistics and administration guarantee audit, quality assurance, and compliance in an online environment. A support organisation that is appropriately resourced and ideally employs instructional designers may support faculties in the conceptualisation and design process of a novel blended learning course [44]. Unfortunately, the novelty of blended learning *"renders institutions unsure of how to afford the educator the support and recognition they give their traditional teachers. For example, performance factors, such as contact hours, academic recognition, and advancement, still militate against blended learning and its e-teachers."* [13]

But what is the right amount of *blending*? This question remains to be controversially discussed [44, 45]. There might not be a universally valid dose-response relationship that dictates the effectiveness of learning, as it depends on the specific topic at the centre of the study and the students' learning habits. An overview of the advantages and disadvantages of different components of blended learning is given below to identify the optimal combination for a given course.

Firstly, one advantage of F2F learning (synchronous, either at present or online) is the familiarity with this type of learning for most undergraduate students. Secondly, as there is personal social interaction, it is likely to be beneficial for developing trustful relationships between students and teachers and among students themselves [45]. Forming and developing such trustful relationships and the teacher's guiding role might eventually lead to optimal student engagement [46]. Thirdly, in a F2F environment, the guidance of students might be more direct and straightforward since both the teacher and students can consider all (verbal and non-verbal) communication. In addition, interaction among students is more easily encouraged when students assemble for the F2F lecture or seminar at the same time and place.

Nevertheless, there are also disadvantages of F2F learning. Importantly, F2F learning is time- and location-constrained, and this could lead to practical issues like time conflicts, possibly resulting in low attendance rates. Secondly, there is a higher risk that this form of teaching shifts to teacher-centred learning, resulting in low involvement and motivation of students. This might eventually lead to suboptimal learning effectiveness between (different cohorts of) students due to poor inter-educator reliability since the quality of a F2F lecture depends, among other things, on the individual motivation of the teacher. Thirdly, the content will often be unavailable after the lesson, as learning material and its content cannot be re-used. Consequently, costs are incurred continually for each seminar.

The other component of blended learning is e-learning. Synchronous or asynchronous e-learning environments have been characterised as more student-controlled and student-centred. Apart from its inherent possibilities to individualise the learning process [14], linkages to external sources of knowledge (e.g., learning games, meta databases, hyperlinks) may also be incorporated. Furthermore, high-quality learning objects, for example, 3D simulations, virtual reality clinical procedures, and video-based interactive branching scenarios, can be implemented modularly, making it feasible to control the cognitive load.

Disadvantages of e-learning may be the limited or missing social interaction and a higher risk of silent drop-outs due to the higher demands on students' self-motivation and self-discipline [21]. Moreover, e-learning challenges the teacher's guidance skills as there are little to no group dynamics. This is because students most commonly work individually with e-learning content at their time and pace. An exception might be *break-out rooms* during synchronous online meetings and lectures where students are directly encouraged to work in groups. Finally, the development of effective online assessments and learning environments is demanding, time- and staff-consuming, and, therefore, challenging to implement successfully.

Since blended learning comprises the advantages of both concepts, F2F learning and e-learning, it potentially can result in effective ways to deliver knowledge. Examples of blended learning concepts have already been shown to be effective in medical [48-50] and dental education [51-54] and are recognised to enhance students' engagement and motivation [45, 47]. The systematic review of Vallée et al. [48], for example, found evidence for the effectiveness of blended learning compared to traditional learning in medical education. Blended learning consistently demonstrated improved effects on knowledge outcomes compared to conventional learning. Bains et al. [55] compared the effectiveness and acceptability of three different teaching concepts (F2F, blended, and e-learning). Their results suggested that the blended learning concept was the most effective and accepted in teaching cephalometric analysis to undergraduate orthodontic students. Especially in diagnostic imaging, e.g., (oral) radiology, primary studies coincide in affirming that blended learning concepts were more effective than traditional F2F concepts and had a positive impact on diagnostic skills [52] and knowledge gain [31]. For example, Durán-Guerrero et al. [49] implemented a blended learning concept in an *"Introduction to diagnostic imaging course"* for teaching radiology and compared the blended learning group of 204 medical students to a F2F control group of 90 medical students. In the blended learning group, five online learning modules were implemented on the local LMS (Moodle). At the beginning and the end of the course, standardised exams and satisfaction surveys at the end of the course were carried out. They compared the final exam scores of both groups and the associated average knowledge gain. The authors concluded that the blended learning concept had a significantly positive impact on students' results in final exams and overall knowledge gain and was also accepted with high satisfaction levels.

1.2 Conceptualisation of an e-learning course

To understand the conceptualisation of an e-learning course, it is necessary to describe the different roles of the e-teacher and the e-learner and to define their tasks.

1.2.1 E-teacher

The most important responsibility of the e-teacher is to design a concept and content that is optimally helping students achieve the intended learning outcomes. Therefore, the content should be optimally adapted to the design to enhance learning effectiveness. This can be achieved by aligning intended learning outcomes, didactic methods, and examination formats, as described in the concept of *constructive alignment* (Fig. 1).

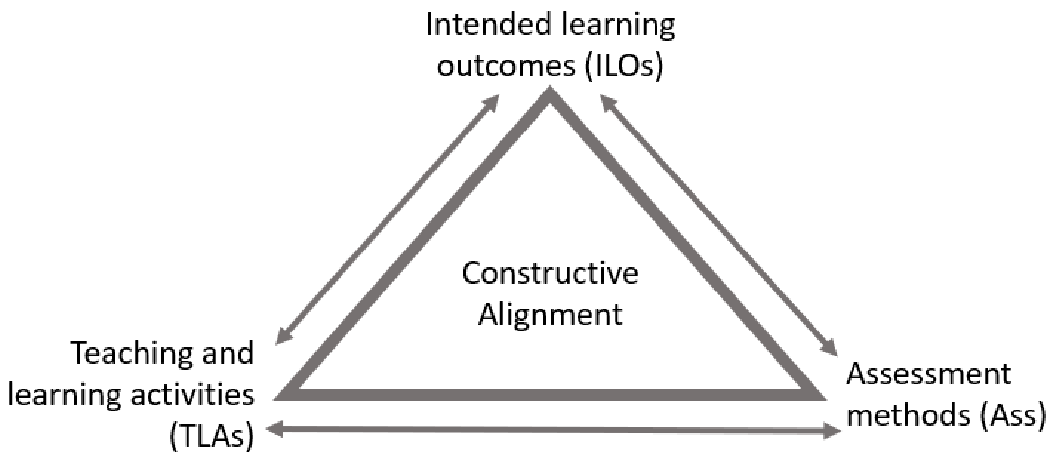

Fig. 1: The concept of *constructive alignment* by Biggs and Tang 2011 [56]

In Germany, the basis for the definition of learning objectives is the national competencies-based catalogue for dentistry (*German: Nationaler Kompetenz-basierter Lernzielkatalog Zahnmedizin*, *NKLZ*). According to the Miller pyramid (Fig. 2), this catalogue contains various competence levels. Competence level 1 corresponds to descriptive, factual knowledge, and competence level 2 describes the ability to explain facts and relationships and place them in a scientific-clinical context. Competence level 3a relates to the ability to apply what has been learned under guidance, and competence level 3b describes the independent and situation-appropriate action, which is usually unattained in undergraduate student teaching. While content at competency levels 1 and 2 is ideally suited for digital video-based e-learning modules (VBLMs), learning objectives in category 3 often require a combination of digital content and hands-on F2F elements.

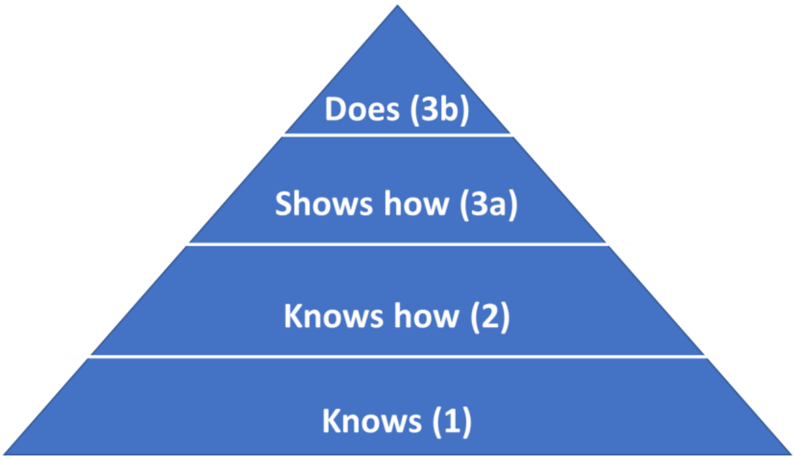

Fig. 2: Competency pyramid according to Miller et al. [57]: The lower levels (1 and 2) correspond to factual and reasoning knowledge. Level 3a is the highest level to be achieved in undergraduate studies.

For the teacher, it is essential to consider the different perspectives, as indicated in Fig. 3. Biggs and Tang [56] suggest that teachers and students hold different approaches to the learning process. On the one hand, teachers think about how the intended learning outcomes are achieved through optimal teaching and learning activities. In contrast, students prioritise the assessment method and align their learning activities accordingly.

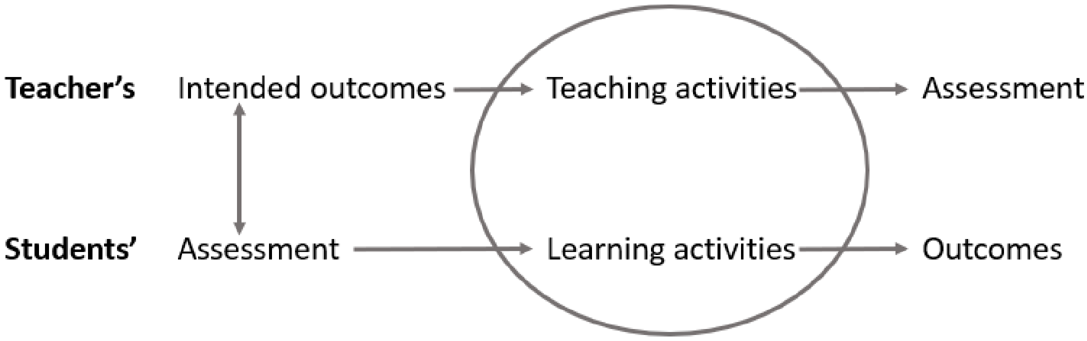

Fig. 3: Teacher's and students' perspectives on assessments by Biggs and Tang 2011 [56]

For designing a student-centred e-learning course, relying on a concept for curriculum development that has been proven successful in medical education might be helpful. The most renowned concept is Kern's six-step approach to curriculum development ([58], 1998, see Fig. 4). It was proposed that medical education curricula are aligned with patients' healthcare needs [58]. This approach received wide recognition and has been adopted by medical educators worldwide. Since then, it has been partially modified to adjust to specific frameworks and environments [59, 60]. Kern proposed that, in order to conceptualise a course successfully, it is essential to sequentially consider six steps, namely the context of implementation, the identification of the problem with a needs analysis, the mapping of objectives and goals, the selection of educational strategies, the implementation itself, and finally, the evaluation and feedback [59, 60].

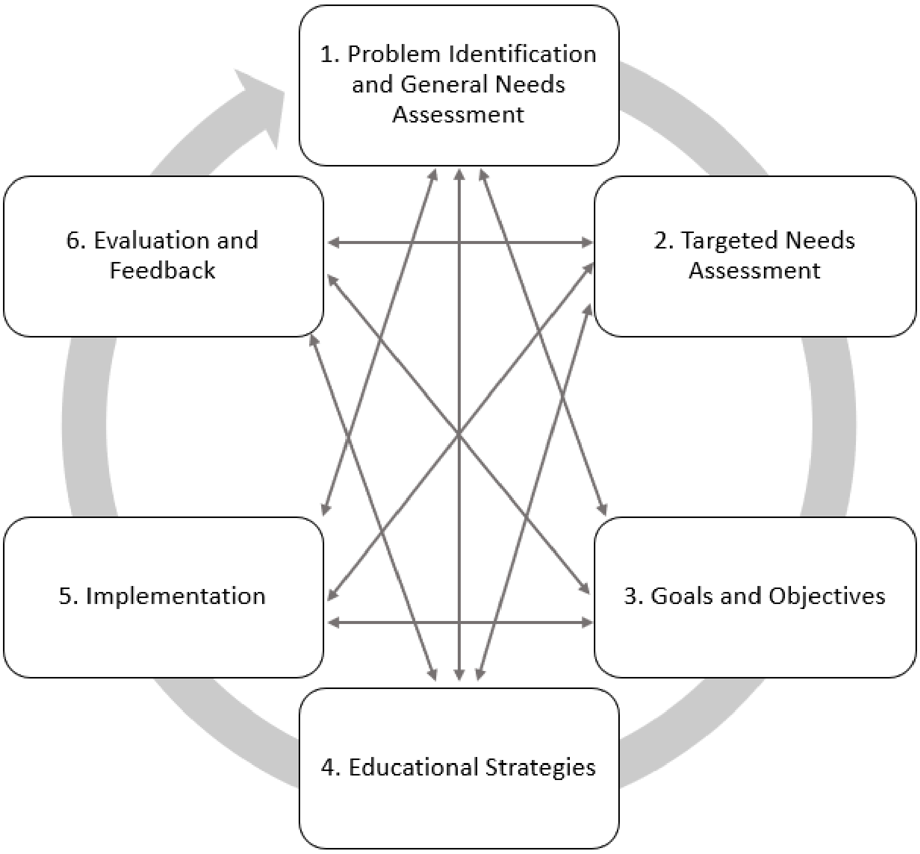

Fig. 4: **The six-step approach to curriculum development by David E. Kern [58]**

Firstly, according to Kern, a problem has to be identified. For example, a health care need, such as the provision of routine dental care. It has to include the current approach to a solution for this problem or need and disclose any deficiencies regarding the training of medical or dental students. Then, an optimal approach to solving the identified problem may be proposed through a general needs assessment. Step 2 comprises a targeted needs assessment that specifies the needs of a specific group of students within a particular learning environment. Next, in step 3, the learning goals and objectives should be mapped and written. Kern states that these objectives *"may include cognitive (knowledge), affective (attitudinal), or psychomotor (skill and behaviour) objectives for the learner"* [58]. Learning objectives are beneficial to comprise content, facilitate suitable methods, and support the learner in defining the focus. Step 4 determines the teaching methods (e.g., buzz groups, interviews with experts, sandwich method, and interactive mind map). Step 5 is the transfer of a theoretical plan to reality: the implementation of the educational concept and its feedback (from colleagues, staff, and students). The support of the faculty, superiors, colleagues, and other internal university departments for teaching, is indispensable here. This might be the most time- and resource-consuming step.

Steps 4 and 5 are decisive for choosing the learning methods and environment. Here it is crucial that steps 1-3 have been meticulously prepared to then select the available technology and subsequently determine the learning concept. As Hoppe et al. [35] emphasised: *"The point is that the learning environment, including such aspects as the roles of learners and teachers, types of activities and physical settings, should not be adapted to the available technology but vice versa."* Finally, in step 6, the performance of the individual student (individual assessment) and the curriculum (called *program evaluation*) is assessed. Assessments and evaluations may either be formative (e.g., voluntary assessments for self-evaluation during learning) or summative (e.g., mandatory assessments to grade or accredit students' learning levels).

Example of a blended learning course

To illustrate the conceptual planning of a blended learning course, I would like to present an exemplary concept, which is adapted from a similar concept by Prof. Birgitte Schoenmakers, proposed in her presentation *"Start to blend and teach: A practice format from the master in Family Medicine"* at the 15th annual meeting of the European Orthodontic Teachers' Forum:

Step	Method	Explanation	Mode
1	Preparatory task	The aim of the online preparatory task is to stimulate the students' motivation and activate their pre-learning.	Online

2	Feedback	For the first 10 minutes of the theoretical lecture (see next point), a short and constructive summarised feedback on the preparatory task is given.	F2F
3	Theoretical lecture	A theoretical lecture aims to give a solid basis of knowledge.	F2F or Online
4	Practical lecture	After the theoretical prerequisite, the previously learned skills are transferred to a practical situation, e.g., problem-based learning (PBL) and patient-oriented learning (POL), where the focus lies on implementation and practice.	F2F
5	Exercise	To consolidate the transfer of theoretical knowledge to the practical activity, an online exercise follows.	Online
6	Workshop	Subsequently, practical exercises in a workshop format are used to routinise the procedure. This workshop is led by peer tutors or postgraduates (peer-assisted learning, for reference, see [61]) and supervised by teachers. It helps to achieve the learning transfer and to maintain the skills.	F2F
7	Feedback	Students are then encouraged to peer-review and give feedback to each other. The aim is that students should learn to observe, evaluate and reflect on a clinical situation and then analyse the situation by asking precise questions [62]. This gives teachers and students formative feedback.	F2F
8	Exercise	In a concluding exercise, learners are encouraged to apply their recently acquired knowledge. (SODOTO=See One, Do One, Teach One [63, 64])	F2F
9	Integrative lecture	In the last short lecture, the teacher integrates all teaching materials and implements a repetition for self-reflection and consolidating knowledge.	F2F or Online

Table 1 Exemplary concept of a blended learning course: The alternation between an online learning and face-to-face (F2F) learning mode with a variety of different didactic methods, e.g., problem-based learning (PBL), patient-oriented learning (POL), or peer-assisted learning.

1.2.2 E-learner

E-learners in higher education are usually adults, which changes the approach to learning compared to children and teenagers. The motivation of adult learners is mainly fuelled by the desire for self-improvement, a need or willingness to learn specific skills, and/or to improve future job possibilities. Adult learners often demonstrate extensive knowledge, expertise, or experience even at the starting point of their learning journey. From a learner's perspective, many different kinds of challenges may occur in the learning process. These challenges arise at different levels and might involve a lack of time and/or (social) support, financial barriers, higher self-reflectiveness, and reduced or decreasing neuroplasticity in later life (neurogenesis) [1].

Regardless of the learning type (e.g., visual, aural, kinesthetic, reading/writing learners) [65], e-learners can be assigned to different learning theories. To support teachers in their selection of learning content and to facilitate evidence-based educational practice [66], it is helpful to have the five major adult learning theories [67] in mind.

1. **Andragogy concept** by Malcolm Knowles [68] defines the *"art and science of helping adults learn."* It is emphasised that adults need to know the reason why to support their internal motivation and how it will benefit them. In contrast to children, adults most likely have a good prior knowledge foundation. They learn much more self-directed and want to take charge. Furthermore, it is suggested that task-oriented learning (learning everyday tasks) is helpful and feasible through more self-directed hands-on experiences and less teacher-led instructions.
2. **Transformative learning** (also called transformational learning) describes a concept by Jack Mezirow [69]. This type of learning mainly describes conscious changes in the thinking process of the learner and adults' perception of their surroundings and themselves. It involves a more reflective approach, including critical thinking and questioning, evaluation of existing beliefs and assumptions, rational process, and finally, reflection of realisation. This might be best suited for complex analytical processes

and long-term personal growth. In sum, this learning process might be described as learning by insight and is based on conscious cognitive processes.

3. **Self-directed or self-regulated learning** describes an adult learning theory by Alan Tough [70] that received much attention during the 1970s. It is proposed that learners take the initiative in their learning by following three steps: planning, execution, and evaluation. This theory has been constantly revised and adopted since its development. For example, Zimmermann et al. [71] described the three steps as task analysis (goal setting, strategic planning), performance phase, and self-reflection phase.
4. **Experiential learning** is a concept developed by David Kolb [71]. It is based on the notion that learning depends on experiences. From this perspective, learning occurs through an active process of doing and reflecting. Therefore, it is a highly individual process for the respective learner. Similar to the andragogy concept, experiential learning is a primarily hands-on learning style. It mainly describes the learning process of mechanical skills and systematic thinking.
5. **Project-based learning** was first described by John Dewey as *"learning by doing"* [67]. It is also sometimes referred to as "problem-based learning" and is connected to real-world scenarios. Until today, this theory is hardly evidence-based but widely used.

With these concepts in mind, it can be concluded that, with adult learners, the regular review of information should be more frequent to compensate for their less plastic brains [72]. The learning content should also be connected to experiences that help to facilitate learning, e.g., hands-on, practical chores, and manual settings. In summary, adult learning should be constructive, cumulative, self-regulated, and situated. Adults already have prior knowledge, are mostly aware of their learning process (metacognition), and are driven by basic needs to a higher motivation to acquire a higher competence, autonomy, and relatedness with peers [73, 74].

In that context, the implementation of e-learning is associated with both possibilities and restraints. E-learning provides easily accessible information that is independent of time and location. Teachers can rapidly update content and, additionally, track user behaviour. This may give new insights into each student's specific learning behaviour, making it possible to edit and update the design and contents according to different learning habits. E-learning provides the opportunity to collaborate, self-exercise, and self-evaluate with the possibility of adding direct feedback. However, the main restrain of e-learning is the difficult integration of practical work processes. This may be of particular relevance in dentistry, a mostly manual and mechanical speciality. However, there are still numerous possibilities to implement e-learning in dentistry to further increase the efficiency of (cognitive) learning. To do so, e-learning has to be easily accessible (e.g., by tablets, smartphones, and computers), should not have too high demands on users' ability, and should always be available. As for availability, digital education may be either synchronous (e.g., live lectures or discussions through online meetings) or asynchronous (e.g., on-demand, pre-recorded content).

To fulfil these demands, effective learning management systems (LMS) have been developed, which are online educational platforms for content delivery. In LMS, synchronous as well as asynchronous differently coded learning materials can be implemented. Due to its familiarity and its well-known user interface, students might get less likely to be distracted from the actual learning process. Particularly, additional support through live chats has been shown to simplify the help-seeking process and thus help the self-regulatory learning process [75]. Additionally, LMS present possibilities for real-time analysis of students' performance, tracking of students' records, support through different communication channels, and easy upgradeability. This means that engaging and interactive content may be developed for an efficient adult learning experience [76].

1.3 E-learning during the COVID-19 pandemic

Due to the coronavirus disease 2019 (COVID-19) pandemic and the rigorous restrictions and social distancing policies enforced in early 2020 to prevent excessive numbers of infections, changes in the structure of the curriculum in higher education were imperative. Within a few weeks, educators all over the world needed to implement different forms of 'emergency education', and entire curricula had to be digitalised to comply with newly developed infection protection laws while at the same time maintaining a high quality of education. Consequently, educational methods shifted from conventional teaching formats to some sort of digital education. For example, F2F lectures were converted to synchronous online lectures, group seminars took place in virtual classrooms, or exercises with patients were transformed into telemedicine consulting hours. Case-based oriented learning was entirely digitalised. This digitalisation proved to be a significant reorganisation of conventional and long-established (teaching) procedures, especially in medical and dental study programs where direct interaction with patients is crucial for the development of clinical competencies.

1.4 Oral radiology courses at the Dental School at Heinrich Heine University Düsseldorf

Even before the COVID-19 pandemic, conventional lectures were combined with an online radiology platform (blended learning concept) for the oral radiology courses at the Dental School of the Heinrich-Heine-University of Düsseldorf (HHU). However, by April 2020, due to the COVID-19 pandemic, all lectures and seminars of the oral radiology courses shifted to online-only formats. In addition, students were provided with VBLMs in their oral radiology courses.

1.5 Ethical Approval

The study was approved under IRB no: 5596 by the ethics committee of the University Hospital Düsseldorf. Before recruitment, verbal and written instructions about the study were provided. Furthermore, all students voluntarily agreed to participate with a consent statement and a declaration of anonymity and confidentiality before the start of the study.

1.6 Aims of Thesis

The present study was partially funded by Heinrich Heine University Düsseldorf for quality enhancement in teaching *(German: Qualitätsverbesserungsmittel für die Lehre*). The goal of the study was to investigate the two different learning concepts and environments in three consecutive oral radiology courses in dental undergraduate training at HHU.

Specifically, this study aimed to:

1. compare the performance in final exams and knowledge gain of undergraduate students in dental radiology courses before and during the COVID-19 pandemic. Thus, traditional F2F blended learning was compared to online-only learning.
2. assess whether the number of additional VBLMs was positively associated with students' skill development by splitting the scores in final exams into questions regarding topics covered by e-learning modules and those not covered.
3. analyse the usage behaviour of students on the online radiology platform.

2 Is online-only learning as effective as blended learning? A longitudinal study comparing undergraduate students' performance in oral radiology, Mücke, K., Busch, C., Becker, J., Drescher, D., Becker, K., European Journal of Dental Education, (2023)

3 Discussion and Conclusion

The purpose of this study was to investigate whether undergraduate students' radiology diagnostic skills were affected by the COVID-19 pandemic. Therefore, we compared an online-only learning concept (synchronous live lectures, online oral radiology platform, VBLMs) that was implemented during the pandemic to a blended learning concept (F2F lectures, online oral radiology platform) that was already established before the pandemic. In addition, we sought to determine whether the number of VBLMs available to students was associated with better performance in final exams. Finally, we analysed the usage behaviour of students on the online radiology platform.

The results indicated a generally high gain of knowledge (at the magnitude of 20 to 30%) during the whole study period, confirming a high efficacy of the overall educational approach. Importantly, the online-only concept (during the pandemic) did not differ from the blended learning concept (before the pandemic) in terms of knowledge gain or performance during the final exams. On the course level, students who received a small number of VBLMs performed slightly worse on exams during the pandemic compared to pre-pandemic semesters. In courses 1 and 2 in the pandemic semesters, the performance in final exams was worse than in pre-pandemic semesters. Moreover, in course 2 (pandemic semester), the knowledge gain was as well lower compared to the pre-pandemic semesters. However, in course 3, no significant difference was observed, neither in knowledge gain nor in performance during final exams when comparing pre-pandemic to pandemic semesters. When analysing the scores from questions covered by the new VBLMs, students in course 1 performed significantly worse during the pandemic, whereas no significant difference was found for courses 2 and 3. When analysing the usage statistics, increased usage of the platform was observed during the pandemic. In general, peak numbers of accesses to the platform were recorded in the days before the final exams.

To our knowledge, this is the first study that systematically examines undergraduate dental students' knowledge gain during the COVID-19 pandemic compared to a pre-pandemic control group. As there is a virtual lack of methodologically sophisticated controlled studies investigating undergraduate students' academic performance or knowledge gain during the COVID-19 pandemic, it is difficult to compare these findings with findings from existing literature. Until now, studies predominantly focussed on the acceptance [77-84] or discussed guidelines for implementation [85-88] of online learning. In the following paragraphs, I will further discuss important issues and considerations regarding the implementation of blended learning and online-only learning concepts.

3.1 Discussion of the different components of the existing learning concepts in oral radiology courses at the HHU

E-learning (asynchronous: oral radiology platform, VBLMs)

Ellaway and Masters [13] stated that "as contemporary medical education increasingly focuses on the application of higher cognitive skills and knowledge in practice, designs for effective medical e-learning need to mirror the dynamics and details of real-world practice." The design of our oral radiology platform, whose effectiveness was established in the study at hand, aligns with the criterion to imitate details of real-life practice since it incorporates a wide range of different radiographs displaying numerous of the most important and most frequent pathologies. Since dentists work with radiographic images as a diagnostic tool on a daily basis, it helps to simplify knowledge transfer and link theory to practice for many students. Especially with additional informational texts combined with the interactive annotation pins, students are able to achieve a more detailed background and gain additional context information (e.g., pertaining to clinical symptoms, differential diagnosis, and treatment concepts).

In a systematic review, Marinopoulos et al. [89] concluded that multimedia, interaction, and repetition enhance the effectiveness of learning in continuing medical education. We achieved this by implementing VBLMs in our local learning management system. To reinforce students' motivation and engagement, a new code (e.g., video as an audio-visual combination) and enhanced multimediality, including animations and video clips, were added. This has been shown to significantly increase the effectiveness of medical education [89]. In contrast, delivering too many different codes of content at the same time might result in cognitive overload in the learner. To prevent cognitive overload, we implemented the VBLMs in time intervals with only one learning module accessible at the same time and sent weekly e-mail reminders to the students.

By increasing the interactivity in the form of formative questions and self-evaluation quizzes with direct feedback at the end of each e-learning module, the learning process and success might have been enhanced as well. Through repetition of content in text-picture combinations, videos, and in quizzes, students were encouraged to reach a higher cognitive level in their learning process.

To increase the learning effectiveness of educational videos, a previous study recommended implementing shorter VBLMs resulting in a shorter processing and engagement time for the students [90] because the median student's attention span (with absolute students' engagement) is shown to be approximately 6 minutes [90]. Interactivity during educational videos might increase attention, especially with advanced learners [91]. Students' attention spans might even tend to decrease over the next years due to the excessive overflow of digital information and content and the multitasking associated with it [92]. Future studies need to investigate the impact of video length on students' knowledge gain.

Overall, previous studies suggested implementing more individualised and student-centred content [84, 85, 93, 94]. Our main focus, therefore, was to create student-centred content that is easy to extend in the future through interactive videos with integrated questions and branching scenarios. The asynchronous e-learning content may also be easily tailored to students' different learning types (e.g., learning mode, learning code, learning interactivity).

One idea for future development is to design an assessment procedure at the beginning of each course or semester that aims to identify their individual learning type and choose the correct learning mode or code accordingly. Additionally, as students work with the e-learning content, *"skip the part questions"* [13] should be implemented; Ellaway and Masters [13] recommend to *"implement pre-assessments or quizzes at the beginning of each learning module. If the students reach a specific result, it is indicated to them which parts and sections they are able to skip."* Furthermore, flexibility in students' use of the e-learning modules is important and contributes to an individualised learning experience. When interrupting and exiting the learning module, students must be able to return to their previous exit point seamlessly.

To further enhance the motivation of students, an individual benchmarking concept could be introduced. One example is to incorporate gamification elements into the learning platform in order for students to collect points or reach milestones and compete with their fellow students on an anonymous ranking list. Gamification functions (e.g., single-choice picture questions, mapping questions, picture-labelling questions, memory quizzes, drag-and-drop questions) are also suitable when improving *"learning behaviours and attitudes towards learning"* [95]. Studies suggest that they can simultaneously increase motivation and thus lead to improved learning outcomes [95-97]. Future models of e-learning in higher education have to adjust flexibly to current developments in order to revise higher education at its core.

F2F lectures (traditional vs synchronous online)

Another part of our blended learning concept at HHU was synchronous F2F lectures. Before the COVID-19 pandemic, these lectures took place in a traditional setting (i.e., live and in person on campus). Since patient cases were presented live most of the time, the proximity to the patients enhanced the emotional learning process. This *human factor* reinforced knowledge retention through emotional involvement and activation [1].

During the COVID-19 pandemic semesters, the faculties aimed to continue teaching as normally as possible, and the synchronous F2F lectures were transformed into an online-only setting. However, this made it difficult to introduce patients to the students. If at all, cases were presented through extra- and intraoral pictures and diagnostic imaging, e.g., panoramic x-rays, cephalometric radiographs, or cone beam computed tomography. To compensate for this deficit, in COVID-19 times, we presented well-prepared patient cases in the VBLMs, in which we reviewed the initial clinical findings, the course of therapy, and also the treatment outcome.

Interestingly, it is recently debated whether there may be an optimal learning receptiveness towards e-learning. It may be the case that learning is most effective when the content is delivered with a certain ‘dosage’ of e-learning. Either exceeding or falling short with digital content during the learning process might impede or inhibit knowledge gain. In other words, the relationship between the amount of digitalised content and knowledge gain might not be a linear *dose-response relationship* but possibly a non-linear, inverted u-shape relationship (similar to the *stress-performance relationship*) [98]. This is an area where further studies might yield valuable insights for future recommendations on synchronous online lectures. It would be intriguing to find out whether there is a cut-off when it comes to the effectiveness of e-learning and whether this cut-off differs between individuals.

3.2 Discussion of the impact of the COVID-19 pandemic

Generally speaking, the COVID-19 pandemic might have had both positive and negative effects on teaching and learning in higher education. The accelerated digitalisation resulted in an increased acquisition of hard- and software, more easily accessible national and third-party funding for e-learning projects, and a forced shift to new and innovative virtual teaching methods, sustainably changing technology use and teaching strategies in medical education. However, the transition to online-only teaching and learning and online learning environments might have also affected students’ (psychological) well-being. Social isolation led to decreased live interactions and increased virtual interaction, possibly resulting in increased psychological distress, insecurities in personal and working environments, and (social) anxiety [99]. Ultimately, this may have had negative effects on learning and, in the end, on academic performance. When interpreting the findings of our or other studies during the COVID-19 pandemic, it is important to keep these COVID-19-related factors in mind.

In line with this, the discussion was raised about another negative effect of online environments: *Zoom fatigue*, which was also called virtual meeting or videoconferencing fatigue [100]. This refers to the negative consequences of the overuse of videoconferencing platforms [101] during the COVID-19 pandemic, a *“stress-related depletion of physiological and cognitive recourses”* [101]. To prompt and standardise further research on this topic, Fauville and colleagues [102] developed and validated the *zoom exhaustion and fatigue scale (ZEFS)*, a 15-item survey with five categories of fatigue: general, social, emotional, visual, and motivational [102]. It has been shown that Zoom fatigue was significantly and positively correlated to anxiety, depression and stress in American employees with a COVID-19-related online shift of their work environment [103] and Turkish university students [104]. Interestingly, even psychotherapists may have suffered from the negative impact of a high frequency of online sessions due to the increased demand for online therapy [105].

Jeremy Bailenson, Professor at the Department of Communication and Education at Stanford University, is one of the leading researchers who extensively investigated Zoom-associated fatigue. In 2021, he outlined four possible underlying causes [106]:

1. *"Eye gaze at a close distance"*: as we use our computers to participate in a Zoom call, sitting a few centimetres away from the screen, we interact at a close distance, already invading a personal space that is "classified as intimate" [106]. He further noted that being stared at for the duration of the Zoom meeting results in physiological distress. Additionally, consequences of the prolonged lasting image fixation may result in eye strain, called asthenopia, possibly including headaches, eye pain, blurred and/or double vision, mental fatigue, and muscle tension [105].
2. *"Cognitive load"*: An increased cognitive load may be caused by *"dedicating cognitive resources to managing the various technological aspects of a videoconference […], for example, image and audio latency"* [106]. A more challenging non-verbal communication, sending and receiving cues, their different meanings in different settings (F2F vs virtual) and difficulties in coordination may result in additional sources of cognitive overload [101].
3. *"An all-day mirror"*: The fact that participants see themselves in a live feed throughout the Zoom meeting, they are more likely to evaluate themselves as it resembles staring into a mirror. On the one hand, it may *"lead to more prosocial behaviour"*, meaning that participants might engage more actively in those meetings. On the other hand, due to increased self-awareness, it can be extremely stressful [106]. As it has been shown that women are more likely impacted by this *"mirror anxiety"* [107], this observation is

of particular interest since dental studies are a women-dominated field in Germany [108].

4. *"Reduced mobility"*: Physical movement decreases as participants are restricted to the camera's view. This reduced mobility has been shown to result in poorer creativity during meetings [109].

Even as the COVID-19 pandemic slowly lapses, Zoom fatigue appears to be a persistent problem in an online-only or e-learning setting. Consequently, further studies might yield valuable insights for future recommendations on online-only learning and working environments. Until now, some solutions have been proposed to mitigate this issue. Firstly, employers, teachers and educators should inquire whether employees, students or participants experience anxiety, fatigue, and depression in connection with their videoconferencing use [103]. Secondly, a blended environment combining F2F meetings and online meetings should be implemented, making the learning environment more flexible and diverse. Since the number of videoconferencing calls positively correlates with higher scores on the ZEFS, the total number of virtual meetings should be reduced, and enough time for recovery between meetings should be scheduled. Thirdly, *"mirror anxiety"* could be reduced by turning the self-window off or introducing digital avatars [110], potentially mimicking the gaze of the Zoom user. Finally, the preference to use audio-only or even phone calls would circumvent the mirror problem and, additionally, give the user the flexibility to increase physical activity.

3.3 Discussion of assessment methods

Knowledge assessment in our study took place on several levels. These included a learning assessment at the beginning of the semester, quizzes with direct feedback within the learning modules, midterm quizzes, and a learning assessment at the end of the semester (final exams). For questions integrated into the learning modules (i.e., questions that covered tooth identification, dental traumatology, dental anomalies, mineralisation disorders, etc.), we aimed to use the *test-enhanced learning effect* [11]. This effect implies that knowledge retention increases when learned material is tested. Especially questions with intermediate difficulty within the learning modules should activate a prompt reflection and support individual learning. These integrated questions and the midterm quizzes were formative assessments giving students the opportunity to self-assess and self-reflect.

This feedback process was enhanced through built-in feedback paragraphs for each question. The exams at the beginning and end of the semester were summative assessments. All exam questions were created through a pre-review process, tested through a peer group in a pilot phase, and then validated in a post-review process (statistical evaluation of difficulty, discriminatory power, reliability, and validity). For future VBLMs, it may be preferable to implement the *test-enhanced learning effect* more deliberately and to ensure more objective and standardised questions by involving additional members of staff and, at best, additional experts from other universities in this process. This might enable a Germany-wide standardisation of the examination questions that is more similar to the standardised medical exams.

The implementation of on-site exams during the first COVID-19 semesters was bureaucratically and organisationally untenable in terms of complying with the strict pandemic-related regulations and restrictions. Hence, the request for a more flexible and remote assessment scenario became imperative. However, it was challenging to address this issue without compromising academic integrity and assessment quality. Concerns that must be addressed when developing remote assessment methods relate to inappropriate/prohibited behaviour (e.g., cheating), privacy issues, a challenge to ensure academically integral questions, and implementation challenges (e.g., difficulties with involved staff and technologies) [111]. Andreou et al. [111] compared exam results of remote and on-site proctoring. A sophisticated proctoring software was used to document inappropriate behaviour by recording sound and image data of the respondents. No significant difference between both assessment methods was found. As the technical infrastructure at HHU was not sophisticated enough at that time, an on-site exam was enabled with a delay of the start of the summer semester in 2020, which resulted in a short 5-week period between the exams at the beginning and end of this summer semester. Despite this limitation, academic integrity and quality throughout all the exams during the pandemic semesters were ensured.

3.4 Discussion of future perspectives

Multimodal Training

Not only in society at large but also in higher education specifically, COVID-19-related restrictions get more and more loosened, and great efforts have been made to return to pre-COVID-19 conditions in many aspects of living. With regard to higher education, the question arose whether an online-only approach is sufficient and sustainable enough to be adapted to the old yet revised curriculum.

There seems to be a major public debate about whether computer-based online-only learning will be the gold standard of all available teaching methods. Interestingly, in the field of cognitive neuroscience, Ward et al. [112] showed that a multimodal learning approach significantly enhanced skill learning in multiple cognitive domains (e.g., *"executive functions, working memory, and planning and problem solving"* [112]) in healthy participants. They found that computer-based online-only learning was inferior to a combination of either physical exercise and/or non-invasive brain stimulation (transcranial direct current stimulation, tDCS). The authors propose that cognitive learning in combination with physical exercise might enhance hippocampal neurogenesis and neuroplasticity, eventually leading to enhanced learning processes and positive long-term effects on a broader set of cognitive abilities [112]. Furthermore, computer-based learning, in combination with tDCS, might further extend and enhance attention and memory [113]. Taken together, these studies suggest that multimodal training stimulates memory and possibly other neurocognitive processes through enhanced hippocampal neurogenesis and, eventually, enhances learning efficiency.

How do these findings relate to the field of dentistry? Since dentistry is a subject that heavily relies on manual skills, cognitive computer-based learning in combination with manual, practical exercises with a patient or demonstrative hands-on equipment would be a feasible and potentially highly effective learning method. For example, in an online-only scenario, it would be possible to enhance simple image-text passages with interactive, hands-on tasks. Furthermore, interactive modules combined with simulation patients or virtual reality simulators could enrich the learning experience. Certainly, any multimodal intervention in learning would be superior to a single intervention modality [112]. We, therefore, plead for the development, integration and implementation of multimodal training and learning strategies in dentistry courses in higher education.

Transfer of training

How can we, as educators and teachers, support students in transferring their theoretical knowledge into everyday practice? There is an ongoing discussion about whether learned skills in one environment can transfer to other situations. On the one hand, some authors suggested that a transfer only occurs if the practice and the transfer task include *"identical elements"* [114]. On the other hand, specific moderators, i.e., variability in training, identical neural circuits, or fundamental abilities, may influence (improve or impede) a transfer of cognitive training [115]. To highlight some of these controversial findings, it has been shown that, for example, working-memory training has little to no effect on *fluid intelligence* (i.e., the ability to solve new problems in different situations). In another study considering the placebo effect, students receiving cognitive training were found to improve their skills just because they assumed there would be an improvement [116]. Interestingly, also action and/or video-game training has been shown to enhance visual and attentional abilities, processing speed, dual-tasking ability, and decision-making. Additionally, identical neural circuits are likely activated during the practised and transfer tasks [115]. However, the applicability (or transfer) of these functional improvements to everyday tasks and life decisions is widely criticised and questioned by many authors, giving a need for more evidence-based research in this regard.

3.5 Conclusion

In conclusion and within the limitations of this study, the evidence suggests that undergraduate dental students at HHU constantly achieved a significant knowledge gain in oral radiology courses throughout pre-pandemic and pandemic semesters. The COVID-19 pandemic and the associated transition to an online-only learning environment did not impair students' performance. Especially students in course 3, who received the highest number of additional VBLMs, tended to improve steadily during pandemic semesters. This study showed that oral radiology content can be learned effectively with well-developed e-learning courses. Online formats seem attractive to teachers and students and should be implemented to complement the post-pandemic oral radiology curriculum [117]. In the future, the existing e-learning content at HHU should be further enhanced with a focus on student-centred content using assessments to identify students' individual learning types, *skip the part questions*, and the *test-enhanced learning effect*. A particularly interesting perspective might be a multimodal combination of e-learning content with physical exercise, hands-on tasks, simulation patients, and virtual reality.

4 References

1. Gluck, M.A., E. Mercado, and C.E. Myers, *Learning and memory : from brain to behavior*. Third edition. ed. 2016, New York: Worth Publishers, Macmillan Learning.

2. Cohen, N.J. and L.R. Squire, *Preserved Learning and Retention of Pattern-Analyzing Skill in Amnesia: Dissociation of Knowing How and Knowing that.* Science, 1980. **210**(4466): p. 207-210.

3. Knowlton, B.J. and L.R. Squire, *Remembering and knowing: Two different expressions of declarative memory.* Journal of Experimental Psychology: Learning, Memory, and Cognition, 1995. **21**(3): p. 699-710.

4. Tulving, E., W. Donaldson, and G.H. Bower, *Organization of memory*. 1972, New York: Academic Press.

5. Jones, G.V., *Misremembering a common object: When left is not right.* Memory & Cognition, 1990. **18**(2): p. 174-182.

6. Bransford, J.D. and M.K. Johnson, *Contextual prerequisites for understanding: Some investigations of comprehension and recall.* Journal of Verbal Learning and Verbal Behavior, 1972. **11**(6): p. 717-726.

7. Craik, F.I.M. and R.S. Lockhart, *Levels of processing: A framework for memory research.* Journal of Verbal Learning and Verbal Behavior, 1972. **11**(6): p. 671-684.

8. Otten, L.J., *Depth of processing effects on neural correlates of memory encoding: Relationship between findings from across- and within-task comparisons.* Brain, 2001. **124**(2): p. 399-412.

9. Butler, A.C. and H.L. Roediger, *Testing improves long-term retention in a simulated classroom setting.* European Journal of Cognitive Psychology, 2007. **19**(4-5): p. 514-527.

10. Roediger, H.L., 3rd and A.C. Butler, *The critical role of retrieval practice in long-term retention.* Trends in cognitive sciences, 2011. **15**(1): p. 20-7.

11. Baghdady, M., et al., *Test-enhanced learning and its effect on comprehension and diagnostic accuracy.* Medical Education, 2014. **48**(2): p. 181-188.

12. Kumar Basak, S., M. Wotto, and P. Bélanger, *E-Learning, M-Learning and D-Learning: Conceptual Definition and Comparative Analysis.* E-Learning and Digital Media, 2018. **15**(4): p. 191-216.

13. Ellaway, R. and K. Masters, *AMEE Guide 32: E-Learning in medical education Part 1: Learning, teaching and assessment.* Medical Teacher, 2008. **30**(5): p. 455-473.

14. Ruiz, J.G., M.J. Mintzer, and R.M. Leipzig, *The impact of E-learning in medical education.* Acad Med, 2006. **81**(3): p. 207-12.

15. Bezemer, J. and G. Kress, *Writing in Multimodal Texts.* Written Communication, 2008. **25**(2): p. 166-195.

16. Farías, M., K. Obilinovic, and R. Orrego, *Implications of Multimodal Learning Models for foreign language teaching and learning.* Colombian Applied Linguistics Journal, 2007(9): p. 174-199.

17. Shridhar, G., A. Pandey, and S. Karmani, *Evaluation of a multimodal teaching method on essential newborn care among health providers at a tertiary care hospital.* Medical journal, Armed Forces India, 2019. **75**(3): p. 303-307.

18. Anastopoulou, S. *Investigating multimodal interactions for the design of learning environments: a case study in science learning*. 2004.

19. Garland, K.V., *E-learning vs. classroom instruction in infection control in a dental hygiene program.* J Dent Educ, 2010. **74**(6): p. 637-43.

20. Grimes, E.B., *Effectiveness of an online course in dental terminology.* J Dent Educ, 2001. **65**(3): p. 242-7.

21. Grimes, E.B., *Student perceptions of an online dental terminology course.* J Dent Educ, 2002. **66**(1): p. 100-7.

22. Gormley, G.J., et al., *Is there a place for e-learning in clinical skills? A survey of undergraduate medical students' experiences and attitudes.* Med Teach, 2009. **31**(1): p. e6-12.

23. Kim, K.J. and G. Kim, *Development of e-learning in medical education: 10 years' experience of Korean medical schools.* Korean J Med Educ, 2019. **31**(3): p. 205-214.

24. Rosenberg, H., M. Sander, and J. Posluns, *The effectiveness of computer-aided learning in teaching orthodontics: a review of the literature.* Am J Orthod Dentofacial Orthop, 2005. **127**(5): p. 599-605.

25. Tan, P.L., D.B. Hay, and E. Whaites, *Implementing e-learning in a radiological science course in dental education: a short-term longitudinal study.* J Dent Educ, 2009. **73**(10): p. 1202-12.

26. Turkyilmaz, I., N.H. Hariri, and L. Jahangiri, *Student's Perception of the Impact of E-learning on Dental Education.* J Contemp Dent Pract, 2019. **20**(5): p. 616-621.

27. Golenhofen, N., et al., *The Use of a Mobile Learning Tool by Medical Students in Undergraduate Anatomy and its Effects on Assessment Outcomes.* Anatomical Sciences Education, 2020. **13**(1): p. 8-18.

28. Maertens, H., et al., *Systematic review of e-learning for surgical training.* Br J Surg, 2016. **103**(11): p. 1428-37.

29. Bock, A., et al., *An innovative PantoDict program for reporting panoramic radiographs using automatic speech recognition in dental education: a randomized observer-blinded study.* Oral Surg Oral Med Oral Pathol Oral Radiol, 2021. **132**(1): p. 104-111.

30. Botelho, M.G., K.R. Agrawal, and M.M. Bornstein, *An systematic review of e-learning outcomes in undergraduate dental radiology curricula-levels of learning and implications for researchers and curriculum planners.* Dentomaxillofac Radiol, 2019. **48**(1): p. 20180027.

31. Meckfessel, S., et al., *Introduction of e-learning in dental radiology reveals significantly improved results in final examination.* J Craniomaxillofac Surg, 2011. **39**(1): p. 40-8.

32. Zitzmann, N.U., et al., *Digital Undergraduate Education in Dentistry: A Systematic Review.* Int J Environ Res Public Health, 2020. **17**(9).

33. Woelber, J.P., T.S. Hilbert, and P. Ratka-Krüger, *Can easy-to-use software deliver effective e-learning in dental education? A randomised controlled study.* Eur J Dent Educ, 2012. **16**(3): p. 187-92.

34. McQuiggan, S., et al., *Mobile learning : a handbook for developers, educators, and learners*. 2015, Wiley: Hoboken, New Jersey.

35. Hoppe, H.U., et al., *Guest editorial: Wireless and Mobile Technologies in Education.* JOURNAL OF COMPUTER ASSISTED LEARNING, 2003. **19**(3): p. 255-259.

36. Eggermont, S., P.M. Bloemendaal, and J.M. van Baalen, *E-learning any time any place anywhere on mobile devices.* Perspect Med Educ, 2013. **2**(2): p. 95-8.

37. Suner, A., Y. Yilmaz, and B. Pişkin, *Mobile learning in dentistry: usage habits, attitudes and perceptions of undergraduate students.* PeerJ, 2019. **7**: p. e7391.

38. Saxena, P., et al., *Assessment of digital literacy and use of smart phones among Central Indian dental students.* J Oral Biol Craniofac Res, 2018. **8**(1): p. 40-43.

39. Rung, A., F. Warnke, and N. Mattheos, *Investigating the use of smartphones for learning purposes by Australian dental students.* JMIR Mhealth Uhealth, 2014. **2**(2): p. e20.

40. Klímová, B., *Mobile Learning in Medical Education.* J Med Syst, 2018. **42**(10): p. 194.

41. Golshah, A., et al., *Efficacy of smartphone-based Mobile learning versus lecture-based learning for instruction of Cephalometric landmark identification.* BMC Med Educ, 2020. **20**(1): p. 287.

42. Bock, A., et al., *Effects of mobile learning on writing panoramic radiograph reports: a quasi-experimental trial in dental education.* BMC Med Educ, 2021. **21**(1): p. 466.

43. Traxler, J., *Distance Learning—Predictions and Possibilities.* Education Sciences, 2018. **8**(1): p. 35.

44. Moskal, P., C. Dziuban, and J. Hartman, *Blended learning: A dangerous idea?* The Internet and Higher Education, 2013. **18**: p. 15-23.

45. Bonk, C.J. and C.R. Graham, *The Handbook of Blended Learning : Global Perspectives, Local Designs*. 2005, John Wiley & Sons: New York.

46. Heilporn, G., S. Lakhal, and M. Bélisle, *Examining effects of instructional strategies on student engagement in blended online courses.* Journal of Computer Assisted Learning, 2022.

47. Heilporn, G., S. Lakhal, and M. Bélisle, *An examination of teachers' strategies to foster student engagement in blended learning in higher education.* International journal of educational technology in higher education, 2021. **18**(1): p. 25.

48. Vallée, A., et al., *Blended Learning Compared to Traditional Learning in Medical Education: Systematic Review and Meta-Analysis.* J Med Internet Res, 2020. **22**(8): p. e16504.

49. Durán-Guerrero, J.A., L.H. Ulloa-Guerrero, and L.C. Salazar-Díaz, *Blended learning: An effective methodology for teaching radiology to medical students.* Revista de la Facultad de Medicina, 2019. **67**(2): p. 273-277.

50. Juliana, A.F., R.C. Mario Luis, and P.B. Maria Lourdes *Blended learning strategies in teaching general pathology at a medical course*. 2017. **53**, 202-209 DOI: 10.5935/1676-2444.20170032.

51. Ullah, R., et al., *Assessment of blended learning for teaching dental anatomy to dentistry students.* J Dent Educ, 2021. **85**(7): p. 1301-1308.

52. Rocha, B.C., et al., *Evaluation of different teaching methods in the radiographic diagnosis of proximal carious lesions.* Dentomaxillofac Radiol, 2021. **50**(4): p. 20200295.

53. Qutieshat, A.S., M.O. Abusamak, and T.N. Maragha, *Impact of Blended Learning on Dental Students' Performance and Satisfaction in Clinical Education.* J Dent Educ, 2020. **84**(2): p. 135-142.

54. Jeganathan, S. and P.S. Fleming, *Blended learning as an adjunct to tutor-led seminars in undergraduate orthodontics: a randomised controlled trial.* Br Dent J, 2020. **228**(5): p. 371-375.

55. Bains, M., et al., *Effectiveness and acceptability of face-to-face, blended and e-learning: a randomised trial of orthodontic undergraduates.* Eur J Dent Educ, 2011. **15**(2): p. 110-7.

56. Biggs, J. and C. Tang, *Teaching for Quality Learning at University*. 2011.

57. Miller, G.E., *The assessment of clinical skills/competence/performance.* Academic medicine : journal of the Association of American Medical Colleges, 1990. **65**(9 Suppl): p. 63-7.

58. Kern, D.E., et al., *Curriculum development for medical education: a six step approach*. 1998: JHU Press.

59. Chen, B.Y., et al., *From Modules to MOOCs: Application of the Six-Step Approach to Online Curriculum Development for Medical Education.* Acad Med, 2019. **94**(5): p. 678-685.

60. Khamis, N.N., et al., *A stepwise model for simulation-based curriculum development for clinical skills, a modification of the six-step approach.* Surgical Endoscopy : And Other Interventional TechniquesOfficial Journal of the Society of American Gastrointestinal and Endoscopic Surgeons (SAGES) and European Association for Endoscopic Surgery (EAES), 2016. **30**(1): p. 279-287.

61. Hofer, M., et al., *Bericht aus der Praxis/Practice Report: How to successfully establish PAL in medical education. 10 tips to succeed in PAL-based courses in undergraduate medical education (UGME).* Z Evid Fortbild Qual Gesundhwes, 2017. **125**: p. 80-84.

62. Bloom, B.S., *Taxonomy of educational objectives : the classification of educational goals / Handbook I, Cognitive domain / Benjamin S. Bloom, editor*. 1956, New York.

63. LeCompte, M., et al., *See one, do one, teach one: A randomized controlled study evaluating the benefit of autonomy in surgical education.* American journal of surgery, 2019. **217**(2): p. 281-287.

64. Khodaverdi, D., *See one, do one, teach one: Is it enough? Yes.* Emergency medicine Australasia : EMA, 2018. **30**(1): p. 107-108.

65. Fleming, N.D. and C. Mills, *Not Another Inventory, Rather a Catalyst for Reflection.* To Improve the Academy, 1992. **11**(1): p. 137-155.

66. Mukhalalati, B.A. and A. Taylor, *Adult Learning Theories in Context: A Quick Guide for Healthcare Professional Educators.* Journal of Medical Education and Curricular Development, 2019. **6**.

67. Arghode, V., E.W. Brieger, and G.N. McLean, *Adult learning theories: implications for online instruction.* European Journal of Training and Development, 2017. **41**(7): p. 593-609.

68. Knowles, M.S., *The modern practice of adult education; andragogy versus pedagogy*. 1970, New York: Association Press.

69. Mezirow, J., *Learning as transformation : critical perspectives on a theory in progress*. 1st ed. The Jossey-Bass higher and adult education series. 2000, San Francisco: Jossey-Bass.

70. Tough, A.M., *The Adult's Learning Projects: A Fresh Approach to Theory and Practice in Adult Learning*. 1979: Ontario Institute for Studies in Education.

71. Kolb, D.A., *Experiential learning : experience as the source of learning and development*. 1984, Englewood Cliffs, N.J.: Prentice-Hall.

72. Bavelier, D., et al., *Brain Plasticity Through the Life Span: Learning to Learn and Action Video Games.* Annual Review of Neuroscience, 2012. **35**(1): p. 391-416.

73. Ausman, J., et al., *How do we learn?* Surgical neurology international, 2021. **12**: p. 298.

74. Bell, C., et al., *How do we learn?* In Practice, 2014. **36**(3): p. 153-154.

75. Broadbent, J. and J. Lodge, *Use of live chat in higher education to support self-regulated help seeking behaviours: a comparison of online and blended learner perspectives.* International Journal of Educational Technology in Higher Education, 2021. **18**(1).

76. Veluvali, P. and J. Surisetti, *Learning Management System for Greater Learner Engagement in Higher Education—A Review.* Higher Education for the Future, 2022. **9**(1): p. 107-121.

77. Quinn, B., et al., *COVID-19: The immediate response of european academic dental institutions and future implications for dental education.* Eur J Dent Educ, 2020. **24**(4): p. 811-814.

78. Al-Taweel, F.B., et al., *Evaluation of technology-based learning by dental students during the pandemic outbreak of coronavirus disease 2019.* Eur J Dent Educ, 2021. **25**(1): p. 183-190.

79. Amir, L.R., et al., *Student perspective of classroom and distance learning during COVID-19 pandemic in the undergraduate dental study program Universitas Indonesia.* BMC Med Educ, 2020. **20**(1): p. 392.

80. Anwar, A., et al., *E-Learning amid the COVID-19 Lockdown: Standpoint of Medical and Dental Undergraduates.* Pak J Med Sci, 2021. **37**(1): p. 217-222.

81. Chang, T.Y., et al., *Effect of online learning for dental education in asia during the pandemic of COVID-19.* J Dent Sci, 2021. **16**(4): p. 1095-1101.

82. Goob, J., et al., *Dental education during the pandemic: Cross-sectional evaluation of four different teaching concepts.* J Dent Educ, 2021. **85**(10): p. 1574-1587.

83. Loch, C., et al., *COVID-19 and dental clinical practice: Students and clinical staff perceptions of health risks and educational impact.* J Dent Educ, 2021. **85**(1): p. 44-52.

84. Patano, A., et al., *Education Technology in Orthodontics and Paediatric Dentistry during the COVID-19 Pandemic: A Systematic Review.* Int J Environ Res Public Health, 2021. **18**(11).

85. Nasseripour, M., et al., *COVID 19 and Dental Education: Transitioning from a Well-established Synchronous Format and Face to Face Teaching to an Asynchronous Format of Dental Clinical Teaching and Learning.* J Med Educ Curric Dev, 2021. **8**: p. 2382120521999667.

86. Bennardo, F., et al., *COVID-19 is a challenge for dental education-A commentary.* Eur J Dent Educ, 2020. **24**(4): p. 822-824.

87. Ather, A., et al., *Coronavirus Disease 19 (COVID-19): Implications for Clinical Dental Care.* J Endod, 2020. **46**(5): p. 584-595.

88. Machado, R.A., et al., *COVID-19 pandemic and the impact on dental education: discussing current and future perspectives.* Braz Oral Res, 2020. **34**: p. e083.

89. Marinopoulos, S.S., et al., *Effectiveness of continuing medical education.* Evid Rep Technol Assess (Full Rep), 2007(149): p. 1-69.

90. Guo, P., J. Kim, and R. Rubin, *How video production affects student engagement: An empirical study of MOOC videos*. 2014. 41-50.

91. Geri, N., A. Winer, and B. Zaks, *A Learning Analytics Approach for Evaluating the Impact of Interactivity in Online Video Lectures on the Attention Span of Students.* Interdisciplinary Journal of e-Skills and Lifelong Learning, 2017. **13**: p. 215-228.

92. Barnes, K., R.C. Marateo, and S.P. Ferris, *Teaching and Learning with the Net Generation.* Innovate: Journal of Online Education, 2007. **3**(4).

93. Olivier, J.A.K. and A. Publishing, *Self-directed multimodal learning in higher education*. 2020, AOSIS: Cape Town, South Africa.

94. Vuchkova, J., T. Maybury, and C.S. Farah, *Digital interactive learning of oral radiographic anatomy.* Eur J Dent Educ, 2012. **16**(1): p. e79-87.

95. van Gaalen, A.E.J., et al., *Gamification of health professions education: a systematic review.* Advances in health sciences education : theory and practice, 2021. **26**(2): p. 683-711.

96. Sarker, U., et al., *Gamification in nursing literature: an integrative review.* Int J Nurs Educ Scholarsh, 2021. **18**(1).

97. Sardi, L., A. Idri, and J.L. Fernández-Alemán, *A systematic review of gamification in e-Health.* Journal of biomedical informatics, 2017. **71**: p. 31-48.

98. Anderson, C.R., *Coping behaviors as intervening mechanisms in the inverted-U stress-performance relationship.* Journal of Applied Psychology, 1976. **61**(1): p. 30-34.

99. Coenen, L., et al. *The impact of COVID-19 on the well-being, education and clinical practice of general practice trainees and trainers: a national cross-sectional study*. BMC Medical Education, 2022. **22**, 1-12 DOI: 10.1186/s12909-022-03174-4.

100. Wiederhold, B.K., *Connecting through Technology during the Coronavirus Disease 2019 Pandemic: Avoiding "zoom Fatigue".* Cyberpsychology, Behavior, and Social Networking, 2020. **23**(7): p. 437-438.

101. Riedl, R., *On the stress potential of videoconferencing: definition and root causes of Zoom fatigue.* Electronic Markets : The International Journal on Networked Business, 2021. **32**(1): p. 153-177.

102. Fauville, G., et al., *Zoom Exhaustion & Fatigue Scale.* Computers in Human Behavior Reports, 2021. **4**.

103. Elbogen, E.B., et al., *A National Study of Zoom Fatigue and Mental Health During the COVID-19 Pandemic: Implications for Future Remote Work.* Cyberpsychology, behavior and social networking, 2022. **25**(7): p. 409-415.

104. Deniz, M.E., et al., *Zoom Fatigue, Psychological Distress, Life Satisfaction, and Academic Well-Being.* Cyberpsychology, behavior and social networking, 2022. **25**(5): p. 270-277.

105. Legerer-Bratengeyer, A., *Zoom-Fatigue managen Die Belastungen des psychotherapeutischen Online-Video-Settings erkennen und einen achtsamen Umgang mit der eigenen Gesundheit pflegen.* Psychotherapie Forum, 2021. **25**(3-4): p. 109-114.

106. Bailenson, J.N., *Nonverbal overload: A theoretical argument for the causes of Zoom fatigue.* Technology, Mind, and Behavior, 2021. **2**(1): p. 1-6.

107. Ingram, R.E., et al., *Self-focused attention, gender, gender role, and vulnerability to negative affect.* Journal of Personality and Social Psychology, 1988. **55**(6): p. 967-978.

108. Bundesamt, S. *Prüfungen an Hochschulen - Fachserie 11 Reihe 4.2 - 2019*. 2020 14.01.2023]; Available from: https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Bildung-Forschung-Kultur/Hochschulen/Publikationen/Downloads-Hochschulen/pruefungen-hochschulen-2110420197004.html?nn=209416.

109. Oppezzo, M. and D.L. Schwartz, *Give your ideas some legs: The positive effect of walking on creative thinking.* Journal of Experimental Psychology: Learning, Memory, and Cognition, 2014. **40**(4): p. 1142-1152.

110. Ratan, R., D.B. Miller, and J.N. Bailenson, *Facial Appearance Dissatisfaction Explains Differences in Zoom Fatigue.* Cyberpsychology, behavior and social networking, 2022. **25**(2): p. 124-129.

111. Andreou, V., et al., *Remote versus on-site proctored exam: comparing student results in a cross-sectional study.* BMC Medical Education, 2021. **21**(1): p. NA.

112. Ward, N., et al., *Enhanced Learning through Multimodal Training: Evidence from a Comprehensive Cognitive, Physical Fitness, and Neuroscience Intervention.* Scientific Reports, 2017. **7**(1).

113. Martin, D.M., et al., *Can transcranial direct current stimulation enhance outcomes from cognitive training? A randomized controlled trial in healthy participants.* The international journal of neuropsychopharmacology, 2013. **16**(9): p. 1927-36.

114. Taatgen, N.A., *The Nature and Transfer of Cognitive Skills.* Psychological Review, 2013. **120**(3): p. 439-471.

115. Boot, W.R. and A.F. Kramer, *The brain-games conundrum: does cognitive training really sharpen the mind?* Cerebrum : the Dana forum on brain science, 2014. **2014**: p. 15.

116. Boot, W.R., et al., *The Pervasive Problem With Placebos in Psychology: Why Active Control Groups Are Not Sufficient to Rule Out Placebo Effects.* Perspectives on Psychological Science, 2013. **8**(4): p. 445-454.

117. Rosa, B., et al., *The COVID-19 post-pandemic scenario to Oral Radiology at Dental Schools.* Oral Radiol, 2020. **36**(4): p. 406-407.

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