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FACULTY OF ELECTRICAL ENGINEERING AND COMPUTING

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Sveučilište u Zagrebu

FAKULTET ELEKTROTEHNIKE I RAČUNARSTVA

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MODEL SUSTAVA ZA POTPORU UČENJU S PROŠIRENOM STVARNOŠĆU U RANOM OSNOVNOŠKOLSKOM OBRAZOVANJU

DOKTORSKI RAD

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ABOUT SUPERVISOR

Prof. Ivica Botički, PhD is a full Professor at the Department of Applied Computing of the University of Zagreb Faculty of Electrical Engineering and Computing (FER). Born in Zagreb in 1981, he graduated Computing at FER in 2004. He did his doctoral studies at FER, receiving his PhD degree in Computing in 2009. He did his postdoc in Educational Technology at the Nanyang Technological University in Singapore in the 2009-2010 period.

He started his professional career at FER in 2004 as an Assistant at the Department of Applied Computing. He was a Research Fellow doing his postdoc at the Nanyang Technological University from July 2009 to September 2010. He was appointed to the professorship track at FER in July 2012, becoming Assistant Professor. In March 2017, he was appointed as an Associate Professor and in October 2020 as a Professor. From September 2018 to June 2019, he was a Visiting Professor at Kyoto University in Japan, from October 2018 to October 2019 a Visiting Scholar at Cornell University in the USA and from October 2020 to September 2021, a Principal Research Fellow at the Nanyang Technological University in Singapore.

As a Professor at FER, he teaches courses relating to software development, algorithms and data structures, and technology enhanced learning at the undergraduate, graduate, and PhD levels, mentors students at all levels and is engaged in a variety of research and industry projects, boards, councils, and initiatives. His research interests include technology enhanced learning, mobile learning, computer supported collaborative learning and learning analytics.

O MENTORU

Prof. dr. sc. Ivica Botički je redoviti profesor na Zavodu za primijenjeno računarstvo Fakulteta elektrotehnike i računarstva Sveučilišta u Zagrebu (FER). Rođen u Zagrebu 1981., diplomirao je računarstvo na FER-u 2004. godine. Doktorske studije je proveo na FER-u, doktoriravši računarstvo 2009. godine. Bio je poslijedoktorand u grani edukacijske tehnologije na Tehnološkom sveučilištu Nanyang u Singapuru od 2009. do 2010. godine.

Profesionalnu karijeru započeo je na FER-u u 2004. kao asistent na Zavodu za primijenjeno računarstvo. Od srpnja 2009. do rujna 2010. bio je poslijedoktorand na Tehnološkom sveučilištu Nanyang. U znanstveno-nastavno zvanje na FER-u je prvi put izabran u srpnju 2012., kada je postao docent. U ožujku 2017. postaje izvanredni profesor, dok je u listopadu 2020. izabran u redovitog profesora. Od rujna 2018. do lipnja 2019. bio je gostujući profesor na Sveučilištu u Kyotu u Japanu. Od listopada 2018. do listopada 2019. bio je gostujući istraživač na Sveučilištu Cornell u SAD-u. Od listopada 2020. do rujna 2021. bio je glavni znanstveni suradnik na Tehnološkom sveučilištu Nanyang u Singapuru.

Kao profesor na FER-u, predaje predmete na preddiplomskim, diplomskim i doktorskim studijima vezane uz programsko inženjerstvo, algoritme i strukture podataka i tehnologijom potpomognuto obrazovanje, mentor je studentima na svim razinama, te je uključen u brojne istraživačke i industrijske projekte, odbore, vijeća i inicijative. Područja istraživanja uključuju tehnologijom potpomognuto učenje, mobilno učenje, kolaborativno učenje i analitike učenja.

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And finally, the author would like to thank his supervisor, Prof **Ivica Botički**, for his mentorship throughout Bachelor, Master and PhD studies and especially throughout the author’s journey through the Technology Enhanced Learning domain.

SUMMARY

In this thesis a novel model for systems supporting learning with augmented reality in early primary education is presented. Gaps in the literature are identified regarding techno-pedagogical maturity of Augmented Reality Learning Experiences (ARLEs), as well as with student engagement, as a proxy predictor of academic success, showing need for further exploration of ARLE engagement benefits or lack thereof. In such experimental exploration, the variable to be isolated is the AR aspect, which is found lacking in previous efforts.

To address those gaps, a model is developed by taking into account affordances considerations for both teachers and students, explored early in the thesis through a developed review rubric for techno-pedagogical maturity of ARLEs. The rubric is used for analysing the maturity of ARLEs reviewed in literature and as a self-assessment tool during model development. Due to the early primary school environment requiring observational instruments to analyse potential effects of ARLE use on student engagement, a new ARLE-adapted instrument based on concerns identified in learning analytics – that is application of relevant theory, design, and data analysis - is presented.

It is then used in a series of experiments through which ARLEs developed in accordance with the model were trialled in the first and second grades of a primary school, with one class receiving an AR experience and another receiving the exact same content in the form of a digital lesson on a tablet computer, allowing isolation of AR as the experimental variable. Data analysis and later focus groups show clear benefits to student engagement in the experimental group, particularly with cognitive engagement, and position ARLEs as best used for review and reinforcement of learned knowledge in lessons.

STRUCTURED SUMMARY IN CROATIAN:

MODEL SUSTAVA ZA POTPORU UČENJU S PROŠIRENOM STVARNOŠĆU U RANOM OSNOVNOŠKOLSKOM OBRAZOVANJU

SAŽETAK

Ova disertacija prezentira inovativni model sustava za potporu učenju s proširenom stvarnošću u ranom osnovnoškolskom obrazovanju. Pregled literature je pokazao nedostatke u postojećoj literaturi u području tehnološko-pedagoške zrelosti obrazovnih iskustava temeljenih na proširenoj stvarnosti, kao i u području angažiranosti učenika (kao indikativne mjere za budući školski uspjeh), pokazujući potrebu za daljnjim istraživanjima o prednostima i nedostacima obrazovnih iskustava temeljenih na proširenoj stvarnosti u vezi s angažiranosti učenika. Uočen je i manjak eksperimentalnih istraživanja koja bi izolirala proširenu stvarnost kao eksperimentalnu varijablu.

Slijedom navedenoga, napravljen je model koji uzima u obzir mogućnosti koje su važne za nastavnike i učenike; provedeno je istraživanje tih mogućnosti kroz razvoj rubrike za recenziju tehnološko-pedagoške zrelosti obrazovnih iskustava temeljenih na proširenoj stvarnosti. Rubrika je upotrijebljena za analizu zrelosti obrazovnih iskustava temeljenih na proširenoj stvarnosti identificiranih u literaturi te kao alat za samoprocjenu zrelosti relevantnih sposobnosti tijekom razvoja modela. Istraživanje ove teme u ranom osnovnoškolskom okruženju zahtijeva promatračke instrumente za analizu potencijalnih utjecaja obrazovnih iskustava temeljenih na proširenoj stvarnosti na angažiranost učenika. Iz tog razloga, razvijen je novi promatrački instrument prilagođen obrazovnim iskustvima temeljenim na proširenoj stvarnosti, na osnovu razmatranja proizašlih iz analitika učenja, koja ukazuju na potrebu temeljenja takvih pristupa na relevantnoj teoriji, dizajnu i pristupima analizi podataka.

Novi instrument je upotrijebljen u seriji eksperimenata tijekom kojih su obrazovna iskustva temeljena na proširenoj stvarnosti, razvijena u skladu s modelom, primijenjena u prvim i drugim razredima osnovne škole u eksperimentalno-istraživačkom pristupu, tako da je jedan razred koristio sustav s obrazovnim iskustvima temeljenim na proširenoj stvarnosti dok je drugi imao istu lekciju s istim materijalima ali prezentiranim kao digitalna lekcija na tablet računalu, izolirajući proširenu stvarnost kao eksperimentalnu varijablu. Obrada podataka i razgovori s fokus grupama ukazuju na jasne prednosti obrazovnih iskustava temeljenih na proširenoj stvarnosti kod učeničke angažiranosti, posebice kod kognitivne angažiranosti, te se preporučuje primjena takvih obrazovnih iskustava kao pomoćnog alata za ponavljanje gradiva lekcija.

UVOD

Proširena stvarnost (engl. *augmented reality - AR*) je naziv za tehnologije koje povezuju stvarni i virtualni svijet tako da proširuju stvarni svijet s virtualnim elementima [1]. Od svojih početaka pronalazi primjenu u obrazovanju [2]. Ponekad se za takve primjene koristi naziv obrazovna iskustva temeljena na proširenoj stvarnosti (engl. *Augmented Reality Learning Experience – ARLE*) [3].

U takvim iskustvima učenici postaju virtualni detektivi koji istražuju neobična oboljenja na plaži [4] ili pad izvanzemaljskog broda [5], uče jezike [6], matematičke koncepte poput simetrije [7] ili znanstvene koncepte poput načina funkcioniranja Sunčevog sustava [8]. Sva navedena iskustva se događaju u stvarnom svijetu tako da je interakcija s virtualnim elementima temeljena na interakciji sa stvarnim svijetom, bilo kroz određivanje lokacije i korištenje stvarne lokacije za određivanje pozicije u virtualnom svijetu ili za učenje određenih virtualnih sadržaja kada korisnik dođe na unaprijed definiranu lokaciju u stvarnom svijetu [4], [5], što se smatra pristupom temeljenom na lokaciji korisnika; bilo tako da računalo putem videokamere prepoznaje predmete u stvarnom svijetu i prilagođava prikazani virtualni sadržaj prema prepoznatom trenutnom sadržaju stvarnog svijeta [6]–[8], što se smatra pristupom temeljenom na računalnom vidu [9]. Tako se virtualni sadržaj čini bliskijim korisniku i stavlja u kontekst njegove stvarne okoline, spajajući i proširujući kontekst virtualnog svijeta s elementima stvarnog te omogućujući da interakcije u stvarnom svijetu utječu na sadržaj virtualnog.

Dosadašnji pregledi područja primjene proširene stvarnosti u obrazovanju ukazuju da postoje indikatori za obrazovnu korist od takvih iskustava [3], [5], [10]. Najčešće primijenjena metodologija istraživanja u ovom području jest istraživanje bazirano na dizajnu (engl. *design based research – DBR*), kojim se obrazovna poboljšanja razvijaju iterativno, s unaprjeđenjima pri svakoj iteraciji te analizom usredotočenom na poboljšanja kroz iteracije [11]. Klasični eksperimentalni dizajn, pri čemu se razvijena obrazovna intervencija primjenjuje na eksperimentalnu skupinu, dok kontrolna skupina dobiva temeljno, neizmijenjeno, obrazovno iskustvo, kako bi se unaprijed postavljena hipoteza mogla potvrditi ili opovrgnuti, nije često primjenjiva u području obrazovnih iskustava temeljenih na proširenoj stvarnosti.

Posljedično, navedeni pristupi pate od nedostatka mogućnosti izolacije proširene stvarnosti kao jasne varijable od sveukupne činjenice da je provedena tehnološka intervencija. Odnosno, nije moguće jednoznačno utvrditi je li do dobivenih rezultata došlo uslijed primjene obrazovnog iskustva temeljenog na proširenoj stvarnosti ili zbog uvođenja tehnologije u do tada klasično obrazovno iskustvo – problem koji je uočen u postojećoj literaturi [3], [12]–[17]. Primjerice, ako se utvrdi da učenici pokazuju veću angažiranost, nije jasno da li ih je na to potaklo prisustvo

tehnologije u obrazovnom procesu ili proširena stvarnost kao karakteristika tehnologije. Stoga je, u sklopu provedenog istraživanja, razvijen sustav koji omogućava dvojaku prezentaciju obrazovnog sadržaja u obliku klasične digitalne lekcije te lekcije temeljene na proširenoj stvarnosti, kako bi se jasno utvrdili prednosti i nedostaci obrazovnih iskustava temeljenih na proširenoj stvarnosti kroz eksperimentalno potvrđivanje s valjanom kontrolnom skupinom.

Takav eksperimentalni pristup je primijenjen u ranom osnovnoškolskom okruženju, s pripadnim karakteristikama ocjenjivanja (vrlo rijetko davanje ocjene drugačije od odlično). Stoga je bilo potrebno primijeniti pristup temeljen na promatranju fokusiran na varijable koje su podložne mjerenju. Rješenje su autor i suradnici pronašli u angažiranosti učenika, zbog njene korelacije s kasnijim obrazovnim uspjehom [18]. Prepoznajemo različite tipove angažiranosti [19], [20]: bihevioralnu (aktivno sudjelovanje u akademskim, društvenim ili drugim obrazovnim aktivnostima), emocionalnu (pozitivne ili negativne reakcije na nastavnike, ostale učenike iz razreda i školu, s time da pozitivne reakcije osnažuju povezanost sa školom i želju za radom) te kognitivnu (smislenost i sistematičnost u pristupu prema školskim zadacima, spremnost za uložiti trud za shvatiti kompleksne ideje ili usvojiti komplicirane vještine).

Pored navedenog problema, mora se uočiti kako obrazovna iskustva temeljena na proširenoj stvarnosti predstavljaju još uvijek relativno novo područje što otvara pitanje, neodgovoreno prije rada autora ove disertacije i projektnih suradnika [21], tehnološko-pedagoške zrelosti područja. Kako bi se tehnološko-pedagoška zrelost utvrdila, potrebno je primijeniti valjane teorijske okvire za utvrditi mogućnosti (engl. *affordances*) koje se trebaju pružiti razrednim dionicima te istražiti da li se iste uistinu pružaju. Kao okvir za utvrđivanje potrebnih mogućnosti za učenike primjenjiv je okvir „Smisleno učenje s informacijsko-komunikacijskim tehnologijama“ [22], prema kojem učenje potpomognuto ICT-om postaje smisleno kada pruža mogućnosti u sljedećim dimenzijama temeljenim na konstruktivističkoj teoriji [23]): aktivnoj (učenici manipuliraju resursima ili objektima i opažaju posljedične fenomene), konstruktivnoj (učenici bi trebali moći konstruirati ideje oko dane tematike kroz proces upita i refleksije), namjere (učenici su oni koji imaju inicijativu i mogućnost za postizanje obrazovnih ciljeva, shvaćanje vlastitog napretka i prilagodbe pristupa), autentičnoj (problemi prezentirani učenicima su iz stvarnog svijeta, sa smislenim kontekstom i realističnom kompleksnosti) i kooperativnoj (fokus je na interakciji i suradnji sa suučenicima za poticanje učenja). Na potrebu za pogledom iz takve perspektive ukazuje više prijašnjih radova u području [3], [24].

S druge strane, potrebno je istražiti i mogućnosti koje se nude nastavniku. Za tu perspektivu, nameće se [25], [26] pitanje opterećenja orkestracijom [7], [27], odnosno da li dana razredna aktivnost zadovoljava sva ograničenja prisutna u razredu, u kojem slučaju dolazi do povećanja

njene obrazovne iskoristivosti. Orkestracija je definirana kao trud potreban da nastavnik provede obrazovnu aktivnost unutar ograničenja prisutnih u razredu. Kako bi se taj potreban trud smanjio, te posljedično povećao izgled da će se zadovoljiti prisutna ograničenja, Cuendet i dr. [7] definiraju pet principa: integracija (ako se podaci lako prenose iz jedne aktivnosti u drugu, nužan trud se smanjuje), opunomoćenje (ako je okolina takva da nastavnik može preuzeti centralnu ulogu kada je to potrebno, nužan trud se smanjuje), svijest (ako nastavnik ima uvid u stanje svih učenika u razredu, nužan trud se smanjuje), fleksibilnost (ako je obrazovna okolina dovoljno fleksibilna da se može prilagoditi evoluciji scenarija i neočekivanim događajima, nužan trud se smanjuje) i minimalizam (ako okolina prikazuje samo ono što je potrebno u danom trenutku, nužan trud se smanjuje).

Na osnovu navedenih pozadinskih činjenica, provedeno je istraživanje prikazano u ovoj disertaciji s ciljem utvrđivanja prednosti, utjecaja na učenike i mogućnosti primjene obrazovnih iskustava temeljenih na proširenoj stvarnosti u ranom osnovnoškolskom obrazovanju.

Pri tome je istraživanje vođeno sljedećim hipotezama:

- Postoji razlika između zrelosti tehnološko-pedagoških mogućnosti koje obrazovna iskustva temeljena na proširenoj stvarnosti pružaju učenicima i koje ta ista iskustva pružaju nastavnicima.
- U ranom osnovnoškolskom obrazovanju moguće je razviti instrument za promatranje angažiranosti učenika temeljen na teorijama o angažiranosti i teorijama o obrazovnim iskustvima temeljenim na proširenoj stvarnosti.
- Primjena obrazovnih iskustava temeljenih na proširenoj stvarnosti utječe na angažiranost učenika i na konstruktivne radnje u ponašanju učenika u ranom osnovnoškolskom obrazovanju.

Znanstveni doprinosi provedenog istraživanja su stoga:

- Specifične metrike za tehnološko-pedagošku zrelost učenja pomoću proširene stvarnosti temeljene na integraciji i prilagodbi postojećih okvira koji uzimaju u obzir potrebe učenika i nastavnika tijekom izvođenja lekcije.
- Algoritmi temeljeni na analitici učenja s primjenom u obradi video zapisa i dnevnika aktivnosti tijekom učenja pomoću proširene stvarnosti u ranom osnovnoškolskom obrazovanju.
- Model sustava za potporu učenju s proširenom stvarnošću temeljen na predloženim algoritmima i njegova verifikacija na studijskom slučaju digitalnih lekcija na tablet-računalima koje koriste proširenu stvarnost u ranom osnovnoškolskom obrazovanju.

PROJEKT, MATERIJAL, ISPITANICI I METODOLOGIJA

Navedena istraživanja su provedena u sklopu projekta „Učenje unutar i izvan škola uz suradnju na mobilnim tablet-računalima“ (SCOLLAm), koji je trajao od 2014. do 2017., odobrenog i financiranog od strane Hrvatske zaklade za znanost pod šifrom UIP-2013-11-7908 koji je imao za cilj, u obliku pilot-projekta, utvrditi primjerene smjernice za učenje na tablet-računalima u hrvatskim osnovnim školama [28]–[30]. Tri glavna područja istraživanja su bila u fokusu: mobilno kolaborativno učenje [31], mobilno učenje s proširenom stvarnošću [32] i mobilno učenje uz igru [33].

Projekt je koristio pristup gdje je pri svakoj lekciji svakom učeniku dodijeljeno tablet-računalo koje je bilo njegovo tijekom lekcije. Taj je pristup odabran jer potiče pozitivni odnos s mobilnim učenjem, omogućujući personalizirano, promišljeno i fokusirano učenje [34].

U sklopu projekta razvijena je platforma SCOLLAm za dizajn i distribuciji digitalnih lekcija kako bi se omogućila prezentacija različitih obrazovnih sadržaja, uključujući klasične digitalne lekcije kao i obrazovna iskustva temeljena na proširenoj stvarnosti, a sve temeljeno na zajedničkoj bazi sadržaja. Svi su sadržaji razvijeni kroz proces iterativnog suradničkog dizajna u koji su bili uključeni istraživači na Sveučilištu u Zagrebu Fakultetu elektrotehnike i računarstva i nastavnici partnerske Osnovne škole Trnjanska u Zagrebu.

U lekcijama sa obrazovnim iskustvima temeljenim na proširenoj stvarnosti takvi sadržaji implementirani su pomoću dva edukacijska modula (AR.Math i AR.Curious) koji su bili pozivani od strane InForm pregledničke aplikacije [28]. Iz korisničkog pogleda, digitalne lekcije su bile prezentirane kao serija interaktivnih prikaznica, koji su mogli sadržavati tekst, grafiku ali i dodatke kroz koje je bilo moguće implementirati upitnike i ostale interaktivne sadržaje. Dodaci su imali pristup bazama sadržaja razvijenim u sklopu projekta.

Moduli proširene stvarnosti pozivani su putem dodatka koji je omogućavao parametrizaciju obrazovnog iskustva temeljenog na proširenoj stvarnosti [35]. Moduli proširene stvarnosti implementirani su na Android i iOS platformama; radi osiguravanja ujednačenog iskustva, pri eksperimentima je korištena isključivo implementacija na Android platformi.

Lekcije odabrane za eksperimente s proširenom stvarnošću su bile iz predmeta Matematika i Priroda i društvo. One su odabrane kao najprikladnije na osnovu diskusije s nastavnicima. AR.Curious je razvijen kao modul prilagođen sadržajima iz kurikuluma Prirode i društva prvog, drugog i trećeg razreda osnovne škole. U AR.Curiousu učenici odgovaraju na pitanja iz teme lekcije putem identificiranja ispravnog predmeta u razredu koji predstavlja odgovor na pitanje. AR.Math je razvijen kao modul prilagođen potrebama Matematike prvog i drugog razreda, gdje učenici odgovaraju na pitanja iz matematike (osnove aritmetike – zbrajanje, oduzimanje,

množenje i dijeljenje) putem papirića s brojevima za brojke desetice i jedinice razasutim po njihovom stolu. Iz navedenog, zaključci koji se donose u sklopu ovdje prezentiranih istraživanja su primjenjivi na rani osnovnoškolski kontekst.

Istraživanje na projektu je provedeno kroz više godina primjenom DBR metodologije, počevši u školskoj godini 2014./2015., tijekom koje su iskustva stečena istraživanjem literature i tijekom preliminarnih istraživanja van projekta [36]–[38] primijenjena za odabir prikladnih sadržaja za istraživanje, u suradnji i kroz diskusiju s nastavnicima OŠ Trnjanska. Također, proveden je pregled literature s fokusom na obrazovne sadržaje temeljene na proširenoj stvarnosti koji su bili primijenjeni u osnovnoškolskom obrazovanju te su razvijeni prototipovi aplikacija koji su testirani s nastavnicima i odabranim učenicima u OŠ Trnjanska.

Tijekom školske godine 2015./2016. provedena su prva istraživanja s ciljem provjere hipoteze da dizajn obrazovnih iskustava temeljenih na proširenoj stvarnosti utječe na akcije i angažiranost učenika, koristeći prve verzije AR.Math i AR.Curious modula. Ta su istraživanja provedena u DBR pristupu tj. moduli su bili unaprjeđivani tijekom godine na osnovu nekoliko ciklusa dizajna i eksperimentiranja. U isto vrijeme je provedena analiza stanja područja u smislu tehnološko-pedagoške zrelosti tijekom koje je razvijena rubrika STAR-ARLE [21].

Tijekom školske godine 2016./2017. finalne verzije AR.Curious i AR.Math modula su bile dostupne te su provedena istraživanja temeljena na eksperimentalnoj metodologiji s ciljem provjere hipoteze da obrazovna iskustva temeljena na proširenoj stvarnosti utječu na angažiranost i konstruktivne radnje osnovnoškolskih učenika nižih razreda. Kako bi se mogla istražiti utvrđena praznina po kojoj su dotadašnji eksperimenti u području provođeni bez dobre kontrolne skupine tj. bez izoliranja proširene stvarnosti kao eksperimentalne varijable, razvijeni su dodaci za SCOLLAm platformu koji koriste iste mehanizme kao moduli za proširenu stvarnost, uključujući i iste sadržaje, ali ih prezentiraju u obliku klasičnih upitnika u digitalnim lekcijama. Serija od 14 eksperimenata je provedena (koristeći proširenu stvarnost i alternativne verzije) kako bi se prikupili podaci za testiranje hipoteze. Obrada prikupljenih podataka provedena je u periodu od 2017. do 2021.

Podaci prikupljeni tijekom istraživanja u 2015./2016. i 2016./2017. šk. god. sastoje se od pozadinskih podataka o učenicima (prikupljenih kroz upitnike koje su nastavnici ispunili), promatranje tijeka lekcija putem video snimanja, intervjua fokus skupina učenika i nastavnika te bilješka opažanja tijekom lekcija. Obrada podataka vršena je primjenom ARLEO instrumenta, razvijenog za tu svrhu na temelju teorije angažiranosti [19], [20] i primjenjivih okvira dizajna [22], [39], kako bi se omogućila analiza podataka na temelju analitika učenja [40], [41]. Podaci su prikupljeni poštujući etička pravila. Prije početka istraživanja u razredu,

potpisan je ugovor s partnerskom školom koji regulira obveze dionika te je prikupljena suglasnost roditelja učenika za sudjelovanje učenika u istraživanjima te za prikupljanje i obradu njihovih podataka. Suglasnost je također dana za promatranje lekcija putem video snimki, softverskih bilježenja radnji te bilješka opažanja. Etičko povjerenstvo Sveučilišta u Zagrebu Fakulteta elektrotehnike i računarstva ocijenilo je projekt SCOLLAm u cjelini sukladnim s etičkim pravilima te ga je odobrilo i dalo dopuštenje za navedena istraživanja.

PREGLED POGLAVLJA

Ova disertacija opisuje istraživanja koja vode prema navedenim znanstvenim doprinosima kroz devet poglavlja, počevši s prvim poglavljem u kojem je dan uvod, utvrđeni problemi i hipoteze koje se istražuju, opisan kontekst projekta i istraživanja uključujući korištene materijale, sudionike i metodologiju. Prvo poglavlje također navodi znanstvene doprinose.

Drugo poglavlje daje pregled korištenja proširene stvarnosti u obrazovne svrhe, kako bi se predloženo istraživanje temeljilo na postojećim postignućima u polju. Pregled počinje s ranim postignućima u devedesetima, te se nastavlja kroz pregled modernih obrazovnih iskustava koja su se pojavila većom dostupnosti pametnih telefona i tablet računala. Analizirani su i prijašnji pregledi područja te se analiziraju teorije analitike učenja i angažiranosti.

U trećem poglavlju se istražuje tehnološko-pedagoška zrelost mogućnosti koje pružaju obrazovna iskustva temeljena na proširenoj stvarnosti. To se čini kroz dokumentiranje razloga za i razvoja Rubrike za procjenu razmatranja značajnih za učenike i nastavnike pri obrazovnim iskustvima temeljenim na proširenoj stvarnosti (engl. *Student and Teacher-relevant considerations' Assessment Rubric for Augmented Reality Learning Experiences - STAR-ARLE*). Rubrika, originalno prezentirana u objavljenom radu autora i suradnika [21], je u skladu s navedenim radom primijenjena za analizu zrelosti područja.

Četvrto poglavlje se bavi prednostima obrazovnih iskustava temeljenih na proširenoj stvarnosti nasuprot tradicionalnih digitalnih lekcija te pitanjem kako ih istražiti u kontekstu ranog osnovnoškolskog obrazovanja. Analizira se angažiranost i postojeći teorijski okviri za angažiranost, uključujući postojeće promatračke instrumente za angažiranost. Istražuje se kako, za angažiranost, popuniti prazninu eksperimentalnog istraživanja obrazovnih iskustava temeljenih na proširenoj stvarnosti u usporedbi s digitalnim lekcijama.

U petom poglavlju, na osnovu prethodnih razmatranja, predlaže se novi promatrački instrument za angažiranost, temeljen na principima analitika učenja [40], [41], prilagođen za promatranje korištenja obrazovnih iskustava temeljenih na proširenoj stvarnosti i digitalnih lekcija u ranom osnovnoškolskom kontekstu, nazvan Promatračkim instrumentom za

obrazovna iskustva koja su temeljena na proširenoj stvarnosti (engl. *Augmented Reality Lessons Engagement Observation instrument – ARLEO*).

U šestom poglavlju, na osnovu prijašnjih razmatranja, razvija se teorijski model sustava za potporu učenju s proširenom stvarnošću u ranom osnovnoškolskom obrazovanju, uzimajući u obzir razmatranja vezana uz tehnološko-pedagoške mogućnosti poželjnih za korištenje od razrednih dionika kao i potrebu da se omogući eksperimentalna usporedba obrazovnih iskustava s i bez proširene stvarnosti. Zatim se opisuje sustav za eksperimentalna istraživanja u SCOLLAm projektu napravljen u skladu sa smjernicama modela.

U sedmom poglavlju se prikazuju rezultati eksperimentalnih istraživanja angažiranosti učenika pri korištenju obrazovnih iskustava s i bez proširene stvarnosti, u cilju potvrde teorijske pretpostavke modela te izolacije bilo kakvih utjecaja obrazovnih iskustva temeljenih na proširenoj stvarnosti na angažiranost osnovnoškolskih učenika nižih razreda. Opisuje se metodologija istraživanja (uključujući primjenu ARLEO instrumenta), dokumentiraju se rezultati promatranja koji su analizirani na temelju kodiranja (sustavnog opisivanja opaženih radnji od strane promatrača koje se zatim sistematiziraju radi omogućavanja statističkih i drugih analiza) putem algoritma ARLEO instrumenta, te se analiziraju povratne informacije dobivene od fokus skupina učenika i nastavnika.

Osmo poglavlje prezentira diskusiju oko razvijenih okvira STAR-ARLE i ARLEO i pripadnih znanstvenih doprinosa. Zaključci o primjeni navedenih okvira su prezentirani i diskutirani, kao i ograničenja proizašla zbog eksternih faktora ali i inherentnih karakteristika provedenih istraživanja. Također je prezentirana diskusija oko sukladnosti SCOLLAm alata s predstavljenim modelom, djelomično analizirana pomoću auto-evaluacije putem STAR-ARLE okvira, te su predložene moguće dorade SCOLLAm alata radi usklađivanja s modelom. Analiza kako bi se ARLEO mogao primijeniti na analizu dnevnika aktivnosti je prezentirana. U konačnici poglavlja, smjerovi buduće dorade i daljnjih istraživanja su predloženi.

U devetom poglavlju prezentirani su zaključci disertacije, utvrđujući kako popunjavaju nedostatke u području, predstavljajući ujedno i konačne doprinose istraživanja.

ZAKLJUČAK

Ova disertacija pridonosi području tehnologijom potpomognutog obrazovanja kroz doprinose razumijevanju obrazovnih iskustava temeljenih na proširenoj stvarnosti. Putem razvijenih alata i eksperimenta tijekom projekta SCOLLAm, pilot-projekta istraživanja učenja na tablet-računalima u hrvatskim osnovnim školama, prezentirana istraživanja pokazuju da obrazovna iskustva temeljena na proširenoj stvarnosti imaju pozitivan učinak na angažiranost

učenika, posebice u kategoriji kognitivne angažiranosti, pri čemu je važno uočiti da se angažiranost učenika povezuje s njihovim kasnijim školskim uspjesima. Pri tome se mora uočiti ograničenje zbog prirode projekta koje ograničava zaključke na rani osnovnoškolski kontekst.

Ti su zaključci bazirani na činjenici da učenici, pored inherentnih mogućnosti koje takva obrazovna iskustva donose, percipiraju obrazovna iskustava temeljena na proširenoj stvarnosti kao igru, ujedno shvaćajući da je to jedan oblik učenja. Učitelji smatraju (a učenici potvrđuju to mišljenje) da je obrazovna iskustva temeljena na proširenoj stvarnosti najbolje koristiti kao alat za provođenje ponavljanja i utvrđivanja gradiva, dok bi inicijalno predavanje trebalo biti prepušteno nastavnicima, osim eventualno u slučajevima vrlo jednostavnih tema.

Gore navedeni zaključci proizlaze iz eksperimenata održanih u 2017. pomoću sustava SCOLLAm, kao utjelovljenja modela sustava za potporu učenju s proširenom stvarnošću u ranom osnovnoškolskom obrazovanju, koji je predložen u ovoj disertaciji. Koristeći naveden sustav, s mogućnostima razvijenim u skladu sa zaključcima o tehnološko-pedagoškoj zrelosti područja, moguće je izolirati proširenu stvarnost kao eksperimentalnu varijablu, s eksperimentalnim razredom koji prolazi kroz obrazovno iskustvo temeljeno na proširenoj stvarnosti i kontrolnim razredom koji prolazi kroz isti sadržaj, ali u obliku obrazovnog iskustva temeljenog na klasičnim digitalnim sadržajima na tablet-računalu. S takvom izolacijom proširene stvarnosti kao eksperimentalne varijable, moguće je donositi zaključke na osnovu dobro utemeljenog eksperimentalnog rada, nešto što je do sada nedostajalo u području.

Kako bi se provela obrada podataka nužna za dolazak do gore navedenih zaključaka, bilo je nužno razviti nove instrumente za promatranje angažiranosti učenika. Razvijen je ARLEO, koji je temeljen na principima analitika učenja i omogućava kodiranje učeničkih radnji tijekom obrazovnih iskustava pomoću dinamički generiranog kataloga kodova konstruiranog pomoću metode konstantne komparacije, što omogućava primjenu u dinamičnim okolinama kakve se obično nalazi prilikom izvođenja obrazovnih iskustava temeljenih na proširenoj stvarnosti, a u kojima se često pojavljuju učeničke radnje koje nisu uobičajene. Kroz korištenje videosnimki kao metode prikupljanja opažanja o tijeku obrazovnog iskustva, ARLEO omogućava detaljno periodičko kodiranje (sustavno opisivanje učeničkih radnji od strane promatrača), omogućujući stvaranje pogleda na obrazovno iskustvo kroz diskretne intervale duge 15 sekundi kroz koje se, za svakog učenika, zna kakva je njegova angažiranost. Na taj način se stvara bogat set podataka kakav je nužan da bi se mogle primijeniti metode znanosti o podacima (engl. *data science*), u skladu s pristupima prisutnim u analitici učenja. Sve poznate kategorije angažiranosti učenika su podržane – kognitivna, emocionalna i bihevioralna, kao i sumarna (prisutnost barem jedne od prijašnjih kategorija) te neangažiranost. To je moguće kroz povezivanje početno kodiranih

učeničkih radnji s fokusiranim kodovima putem kojih ih se povezuje s kategorijama angažiranosti. Fleksibilnost koju omogućuje tako detaljno kodiranje je rezultat ulaganja značajnog vremena u proces kodiranja od strane visoko kompetentnih istraživača.

Prikazani model sustava za potporu učenju s proširenom stvarnošću u ranom osnovnoškolskom obrazovanju temelji se na distribuiranoj arhitekturi, sa jezgrom razvijenom u skladu s pristupima sustava za potporu učenju, dok su moduli za obrazovna iskustva temeljena na proširenoj stvarnosti tek jedan od načina prikaza generičkih obrazovnih sadržaja. Taj je pristup odabran na osnovu analize mogućnosti koje obrazovna iskustva temeljena na proširenoj stvarnosti nude nastavnicima, gdje je utvrđeno da je zrelost takvih mogućnosti niska, što zahtjeva njihovo poboljšanje integracijom sa sustavima za potporu učenju.

Zaključci o zrelosti obrazovnih iskustava temeljenih na proširenoj stvarnosti, iz tehnološko-pedagoške perspektive, temeljeni su na detaljnoj analizi dostupne literature putem razvijene STAR-ARLE rubrike, koja omogućava analizu takvih obrazovnih iskustava iz kombinacije perspektiva – s jedne strane, iz perspektive mogućnosti bitnih za smisleno učenje učenika, te s druge strane iz perspektive mogućnosti nužnih da se smanji orkestracijsko opterećenje nastavnika. Utvrđeno je da takva obrazovna iskustva često imaju dobru razinu mogućnosti usmjerenih na učenike, dok je razina mogućnosti usmjerenih na nastavnike niska, jer ih je teško integrirati i učiniti dijelom dobro vođenih i dobro orkestriranih lekcija.

Zaključci u ovoj disertaciji su ograničeni prirodom projekta tijekom kojeg su istraživanja provedena. SCOLLAm je bio pilot-projekt s ciljem započinjanja istraživanja ovog područja u Hrvatskoj - bio je ograničen na suradnju s jednom osnovnom školom, što jasno dovodi do ograničenog uzorka. Iako je taj uzorak potvrđen kao statistički signifikantan, nije moguće otkloniti potencijalne utjecaje na rezultate proizašle iz konteksta projektne škole. Također, takav uzorak ograničava zaključke na kontekst ranog osnovnoškolskog obrazovanja. Zbog ograničenih resursa, nije bilo moguće u SCOLLAm sustav implementirati sve mogućnosti koje teorijski model predviđa. Stoga, nada je autora da će buduća istraživačka stremljenja u području upotrijebiti ovdje prikazane rezultate i razvijene instrumente kao temelj za proširenje istraživanja mogućnosti koje obrazovna iskustva temeljena na proširenoj stvarnosti nude.

Nada je da će razvijeni instrumenti biti od koristi dizajnerima obrazovnih iskustava temeljenih na proširenoj stvarnosti i da će im omogućiti saznanja o zrelosti razvijenih iskustava putem korištenja STAR-ARLE rubrike kao alata za samoprocjenu. Također se nada da će ARLEO instrument pomoći u primjeni fleksibilnih pristupa temeljenih na promatranju pri prikupljanja podataka za potporu su-dizajna lekcija s nastavnicima putem iterativnog pristupa istraživanju kao dijela istraživanja temeljenog na dizajnu.

KEYWORDS

augmented reality, experiment, observation, engagement, primary education, qualitative research, tablet, model, techno-pedagogical maturity, meaningful learning, orchestration load, learning analytics

KLJUČNI POJMOVI

proširena stvarnost, eksperiment, promatranje, angažiranost, osnovnoškolsko obrazovanje, kvalitativno istraživanje, tablet računalo, tehnološko-pedagoška zrelost, smisleno učenje, opterećenje orkestracijom, analitike učenja

CONTENTS

1. INTRODUCTION

1.1. Augmented reality as an aspect of modern mobile learning

Augmented Reality (AR) is the name for technologies on the reality-virtuality continuum connecting the real and virtual worlds by augmenting the feedback of the real world with virtual elements [1]. Since its beginnings it has found application in the field of education [2]. For those applications, the term Augmented Reality Learning Experience (ARLE) is sometimes used [3].

During the 2010s, Augmented Reality has seen a boom due to the wide deployment of smartphones and tablets enabling almost everyone to have in their pocket or bag a device which can be effectively used for enabling AR-enhanced experiences, as it has a camera, GPS sensors, gyro-compass sensors, and others, combined with sufficient processing and graphical capabilities [42]. Industry reports indicate interests in those experiences outside of the traditional (mobile) gamer spheres, highlighting the immersive reality escapism as something of interest to non-gamers as well [43].

ARLEs have kept pace with said developments. Students can become virtual detectives who investigate strange illnesses at a beach [4] or a crash of an alien spaceship [5], learn languages [6], learn about mathematical concepts such as symmetry [7] or scientific concepts such as how the solar system functions [8]. All the described experiences are anchored in the real world by the fact that the interaction with the virtual elements is based on interaction with the real world. This can be either through determining the location of the user in the real world and using it to position the user in the virtual world and/or to trigger learning of certain virtual materials when the user is at a predefined real-world location [4], [5], those being considered location-based approaches. Alternatively, the interaction between the real and virtual world can be through the computing device (via camera) recognising certain objects (markers) in the real world and adjusting the displayed virtual content to the current recognised real-world content [6]–[8], those being vision-based approaches [9]. In that way, virtual content is brought closer to the user and contextualized with their actual surroundings, connecting, and expanding the contexts of the real and virtual worlds and enabling interactions in the real world to affect the content of the virtual world.

The existing reviews of the usage of AR in education show that there are indicators for educational benefit of such usage [3], [5], [10]. The applicable research methodology in this field is design-based research (DBR), by which the educational improvements are developed iteratively, with enhancements with each iteration and analysis focused on improvements through iterations [11]. Classic experimental design, in which researchers group subjects into the experimental and control groups, with the developed educational intervention being applied to the experimental group, while the control group receives the baseline technological educational experiences with the same educational contents is not often applied for ARLEs. The closest variant commonly used is that the control group uses digital lessons with differing content to the one presented in the ARLE.

Consequently, the described approaches suffer from the inability to isolate AR as a clear variable compared to the fact that a technological intervention has been made. I.e., it is not possible to clearly establish if the results are there due to the application of the ARLE specifically or due to implementing technology into the classic educational experience in general. For example, if the results show that students are more engaged, it is not clear if this was encouraged by the presence of technology in the educational process or specifically by AR as technological intervention approach – an issue recognised in the literature [3], [12]–[17]. Therefore, as part of the conducted research, a system was developed that enables the parallel presentation of educational contents in the form of both a classic digital lesson as well as an ARLE, to clearly establish the advantages and disadvantages of ARLEs through an experimental approach with a valid control group.

Such experimental work was done in the early primary school setting. With the attendant issues of grading (grades are assigned by teachers more for motivational and pedagogical effect rather than as an objective assessment of displayed knowledge), an observational approach focused on measurable relevant variables needed to be applied. For this, the author and collaborators turned to student engagement, due to its correlation with later academic success of students [18]. Different types of engagement are recognised [19], [20]: behavioural (active participation in academic, social or other educational activities), emotional (positive or negative reactions to teachers, classmates and the school, with positive reactions strengthening the connection with school and willingness to work) and cognitive (thoughtful and systematic approach to school tasks, willingness to put in the effort needed to understand complex ideas or to master complicated skills).

Aside from the issue of correctly isolating the advantages and disadvantages of ARLEs, it must be noted that ARLEs still represent a fairly new development, which opens the question, unresolved prior to the work of the author, of the techno-pedagogical maturity of the field. As the framework for determining the necessary maturity of capabilities for students the Meaningful Learning with ICT framework was chosen [22], according to which learning supported by ICT becomes meaningful when it offers affordances to students necessary for their observation and meaning making in regards to phenomena, grounded in their pre-existing knowledge of the real-world and cooperative efforts, in line with constructivist theory [23]. The need for such a perspective is indicated in multiple previous works in the field [3], [24].

On the other hand, it is necessary to determine the maturity of capabilities offered to the teacher [44]. For that perspective, a suitable approach [25], [26], and the one chosen for this study, is Orchestration Load [7], [27]. It answers the question if the given classroom activity fulfils all constraints present in the class, leading to increased educational usability. Orchestration is defined as the effort needed for the teacher to perform the educational activity within the constraints present in the classroom [27].

1.2. Problem statement

Based on the presented overview, and as further developed in the following chapters, the research conducted, both theoretical and in the field, had the objective of determining advantages, effects on students and possibilities for applying Augmented Reality Learning Experiences (ARLEs) in primary school education.

In this, the following hypotheses of research were examined:

- There is a difference in maturity of techno-pedagogical affordances provided by ARLEs to students and teachers.
- In early primary school education, it is possible to develop valid algorithmic observational instruments for examining student engagement that are grounded in learning analytics, engagement and ARLE theory.
- The application of ARLEs affects early primary school student engagement and constructive actions.

1.3. Project context, materials, participants, and methodology

The context of the conducted studies is the Croatian Science Foundation's scientific project "Opening up education through Seamless and COLLAborative Mobile learning on tablet computers" (SCOLLAm, from 2014 to 2017) - UIP-2013-11-7908 - which had as a goal to determine appropriate approaches for learning on tablet computers in Croatian primary schools [28]–[30]. Three main research areas were examined: mobile collaborative learning [31], mobile augmented reality learning [35] and mobile gamification [33].

Project SCOLLAm was conducted utilizing the approach of 1:1 ratio between tablet-computers and students; that is, each student had their own tablet-computer available for participating in the ARLE. Such an approach has been decided upon as it encourages mobile learning, enabling personalized, deep, and focused learning [34].

As part of the project the SCOLLAm platform for design and delivery of digital lessons was developed to enable use of differing educational contents, including classic digital lessons as well as ARLEs, with a common content database. All contents were developed through an iterative co-design process by the research staff at the University of Zagreb Faculty of Electrical Engineering and Computing and the teachers at the partner primary school.

Augmented Reality has been implemented through educational modules (AR.Math and AR.Curious) which were utilized via the InForm viewer application in lessons using AR modules [28]. From the user perspective, digital lessons were presented as a series of interactive slides, which typically contain text, graphics, as well as widgets through which it is possible to implement questionnaires and other interactive contents. Widgets had access to the content databases developed as part of the project.

Calls to the AR modules were done through a special type of widgets with parameters being passed to the modules through which the ARLE is parametrized [35]. AR modules were implemented on Android and iOS platforms; however, to have a consistent experience for all students only the Android platform was used during experiments.

Contents chosen for use in AR experiments were educational lessons in Mathematics and Nature and Society subjects. Those contents were chosen as the most suitable based on discussion with teachers. AR.Curious was a module adapted for Nature and Society contents for 1st, 2nd and 3rd grades and it offers an experience during which students answer thematic questions by identifying the correct object in the classroom which represents the correct answer to the question. AR.Math was a module adapted for Mathematics contents for 1st and 2nd grades, where students answer mathematics questions through paper markers on their work desk. Therefore, the conclusions about ARLEs based on the conducted research are appropriate for the early primary school context (lower primary school grades).

To utilize the developed system in practice and to experimentally confirm the listed hypotheses, cooperation with Primary School Trnjanska was established; the subjects were the following grades (note: nominal numbers on the number of students in school year 2016/2017 are listed; in practice, there was fluctuation during the school years – the exact numbers of participants for each experiment are listed in the detailed methodology presented in chapter 7):

- 1A grade (2015/2016) – 2A grade (2016/2017) – 18 students
- 1B grade (2015/2016) – 2B grade (2016/2017) – 17 students

Research and data collection was conducted iteratively based on the DBR methodology. Based on conducted literature review and experiences gained during initial research [36]–[38], initial discussions and analysis were done at the beginning of the SCOLLAm project in academic year 2014/2015 with teachers of Primary School Trnjanska in order to select appropriate contents for use in the experiments. Additionally, a literature review was conducted with a focus on ARLEs for primary school, prototype versions of SCOLLAm applications were developed and their initial testing in cooperation with teachers and selected students at Primary School Trnjanska was done.

During the academic year 2015/2016 first experiments were conducted with the goal of examining the hypothesis of the effects of design approaches on student engagement and actions, utilizing the AR.Math and AR.Curious modules. Those experiments were done utilizing the DBR methodology; that is, the modules were incrementally improved through several design and experimentation cycles in the spring of 2016. Furthermore, an analysis of the state of the field was done and a framework (STAR-ARLE) for determining the techno-pedagogical maturity of ARLEs developed, testing the linked hypothesis. The results were published in [21].

During the academic year 2016/2017 the final versions of modules AR.Curious and AR.Math became available and experiments using the experimental methodology were devised to test the hypothesis that "the application of ARLEs affects early primary school student engagement and constructive actions". As needed as part of the experiment, considering the background discussion about the need for a viable control group, widgets for the SCOLLAm platform were developed which do not utilize AR technology, but offer the same contents as AR.Curious and AR.Math as classic digital lessons. A series of 14 experiments was done (either testing the classic digital lesson version or the ARLE version of a lesson) to gather data to test the hypothesis. The data analysis and preparation for publication was done in the period of 2017 – 2021.

Data gathered during the experiments in 2015/2016 and 2016/2017 consists of background data on students (gathered through teacher questionnaires), lesson observation via videorecording, teacher and student focus group interviews and lesson observation notes. Data processing is based on video coding to be interpreted utilizing the Augmented Reality Lessons Engagement Observation instrument (ARLEO), developed for this purpose on the basis of engagement theory [19], [20] and applicable design frameworks [22], [39] in order to allow for learning analytics-based [40], [41] data analysis of the results of the experiments.

1.4. Scientific contributions

Based on the conducted research, this thesis lays out the work done to develop the following scientific contributions that address gaps in the current understanding of ARLEs, in how they operate in an early primary school classroom (i.e., formal learning) educational environment:

1) Specific metrics for techno-pedagogical maturity of learning with augmented reality based on integration and adaptation of existing frameworks which consider the requirements of students and teachers during lesson execution.
2) Algorithms based on learning analytics with application in video records and activity logs processing in learning with augmented reality in early primary education.
3) Model of a system for supporting learning with augmented reality based on the proposed algorithms and the identification of advantages and disadvantages of digital lessons for tablet computers that use augmented reality in early primary education.

1.5. Chapter overview

This thesis develops the above defined scientific contributions through the following seven chapters, with conclusions given as chapter 9. An overview, focusing on the major theoretical bases to the contributions and the contributions themselves, is given in Fig. 1.1.

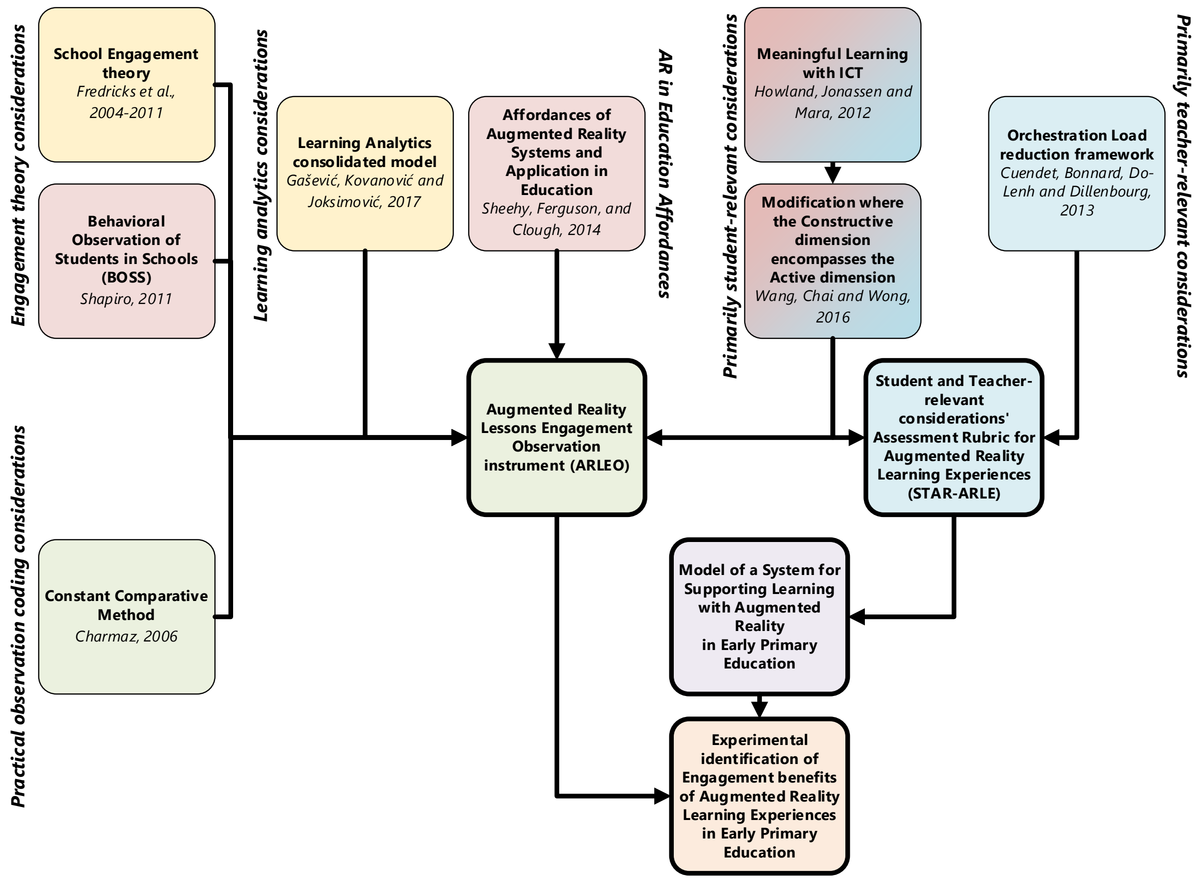

Fig. 1.1. Overview of the major theoretical bases for this thesis and their contribution to the scientific contributions of the thesis. Expanded from Fig. 1 in [21].

In chapter 2, an overview of educational use of AR is given, to ground later examinations in existing work in the field. The overview starts with early developments in 1990s, through examination of more modern approaches after the rise of smartphones and tablets in the 2000s.

The background to the highly relevant theory of learning analytics and engagement is further given, to ground later analysis in a solid theoretical background. In Fig. 1.1 the theoretical bases analysed in chapter 2 are shaded in gold colour.

Chapter 3 provides the examination of the maturity of techno-pedagogical affordances of ARLEs for all classroom stakeholders by documenting the reasoning for and development of the Student and Teacher-relevant considerations' Assessment Rubric for Augmented Reality Learning Experiences (STAR-ARLE), which provides for specific metrics for techno-pedagogical maturity of learning with augmented reality based on integration and adaptation of existing frameworks which take into account the requirements of students and teachers during lesson execution. It shows as well its application to examine the maturity of the field, as previously examined in the author and collaborators' published work [21]. In Fig. 1.1 the theoretical bases and the related contributions analysed in chapter 3 are shaded in blue colour.

Chapter 4 delves into the question of educational benefits of ARLEs and how to best examine them in the early primary school context versus classical digital lessons by examining the existing frameworks (non-ARLE related) for examining engagement, including engagement observational instruments. It explores the issues of how to address the experimental comparison gap of AR versus non-AR digital lessons in terms of advantages and disadvantages, through the lens of engagement. In Fig. 1.1 the theoretical bases analysed in chapter 4 are shaded in red colour.

Based on those examinations, in Chapter 5, a new observational instrument for engagement, based on developed algorithms based on learning analytics with application in video records processing in learning with augmented reality in early primary education, is proposed, named the Augmented Reality Lessons Engagement Observation instrument or ARLEO. In Fig. 1.1 the theoretical bases and the related contributions analysed in chapter 5 are shaded in green colour.

In chapter 6, the previous considerations are brought together to define a theoretical model of a system for supporting learning with augmented reality based on the proposed algorithms. The system model is defined considering the previous considerations of techno-pedagogical affordances for classroom stakeholders as well as to enable engagement observation in AR and non-AR modes. The instantiation of the model used for experimental work is then presented. In Fig. 1.1 the contributions analysed in chapter 5 are shaded in purple colour.

In chapter 7, the experimental work with the SCOLLAm platform to examine engagement with ARLEs versus non-AR digital lessons in early primary school education is examined, to both validate the model and isolate the engagement effects of ARLEs in early primary school education. The methodology of the experimental work is described (including the use of the developed ARLEO observational instrument), observational results documented, and analysed utilizing learning analytics approaches. In Fig. 1.1 the contributions analysed in chapter 3 are shaded in orange colour.

Chapter 8 provides a discussion of the presented developed frameworks and the related scientific contributions, starting with STAR-ARLE and continuing with ARLEO. A discussion about the results for each of the instruments is had and finally conclusions regarding engagement in this context provided, identifying the advantages and disadvantages of digital lessons for tablet computers that use augmented reality in early primary education. Additionally, discussion is had regarding the system used for the research, it being compared against the presented theoretical model, where it is assessed for techno-pedagogical affordances with STAR-ARLE. This is followed by a discussion, with examples, of how certain aspects could be improved towards the ideal theoretical model. Limitations of the presented developed frameworks and conducted research, both due to external factors as well as analysing systemic issues inherent to the methodology, are presented. Finally, an analysis is made on how ARLEO could be applied to activity log processing.

Chapter 9 presents the conclusions of this thesis, interconnecting and analysing in aggregate the conclusions of the various work done in the field as part of the SCOLLAm project, in how it addresses the gaps identified in the field, what are the resultant findings and what are potential future directions for research arising out of the work.

2. BACKGROUND ON RELEVANT TOPICS FOR THE EDUCATIONAL USE OF AR

2.1. Early developments of AR

Educational use of AR systems has a long history, with complex specialized early ones existing since the 1990s [2]. Early ARLEs were specialized, typically for lifelong learning in vocational or professional fields (a domain of ARLEs very active today as well in a much more refined versions [45]) where specialized equipment could be fielded by well-funded organisations, as the equipment was expensive and bulky. From those early efforts, there are examples of use for medical training [46] and for training and assisting in airline manufacture [47], as examples.

The second wave of ARLEs happened in the 2000s with the deployment of early PDA devices which indicated potential future developments with their deployment in the field of mobile computing devices with multi-sensor capabilities, bringing the technology into the classroom. In this wave, we can see pioneering examples such as *Alien Contact!* [5], where students learn topics related to mathematics, language arts and scientific literacy to solve the mystery scenario of an alien crash-landing through exploration in a field near the school of artefacts underpinned by a location-based ARLE which triggers based on student location within the field. It represents an early ARLE in the investigation style based on the location-based approach, which was a common approach in this phase [4], [48].

At the same time, vision-based ARLEs based on PCs and relatively commodity custom head-mounted display technology started to become available such as with the *Live Solar System* [8] which used the basic vision-based approach of identifying markers to display (overlay) virtual information about the solar system and the relationships therein based on the identified markers.

2.2. Modern approaches to ARLEs

The main technological push for ARLEs came through the rise of smartphones and tablet computers in the 2000s. With the proliferation of those mobile devices that contain good 3D rendering capabilities and computational power as well as a multitude of sensors such as cameras, gyroscopes and GPS locations services, all in a compact, easy to use and integrated package, AR systems could be detached from the use of specialized systems to the use of commodity mobile computing hardware, spurring both their wide acceptance amongst all age groups but especially younger ones [42], [43] in a variety of fields, including in ARLEs [10].

In this phase, we can see an explosion of applications, from AR-enhanced books that pop-up virtual elements on actual illustrations in the book [49]–[53], through learning about art with enhanced materials at an art course [54] or through an AR-enhanced art history tour of Florence [55], learning language in the classroom [6], learning science concepts [56]–[58] or history and humanities [59].

While the mass deployment of tablets and smartphones has led to democratization of ARLEs, allowing for significantly broader deployment than previously, more refined ARLEs based on specialized hardware can also be observed in this phase, such as ARLEs for learning carpentry, symmetry and logistics [7], earth sciences [60] or learning about natural, social and cultural environment [61].

2.3. Reviews of ARLEs

To systemize the view of ARLEs on a high level, it is necessary to observe what considerations are taken into account by reviewers when performing reviews of ARLEs. For this purpose, a literature review was performed in 2016 (leading ultimately to [21]), identifying the following previous reviews of ARLEs.

Early efforts at review can be characterised as exploratory of a new field, such as Specht et al.'s 2011 work [62], which explored the up-to-then ARLEs in the context of interaction design and educational patterns, in order to analyse educational user contexts in ARLEs. Similarly, Yuen et al. [63] provide an early overview and speculate on future developmental directions. The early seminal review work in the field is the 2012 Billinghurst and Duenser paper [10] which introduced the question of educational benefits of the field for the first time systematically in literature by reviewing early efforts through a feature-based classification and attempting to present preliminary educational benefits reporting. A year later, Wu et al. [64] classified then-existing ARLEs based on their emphasis of roles, locations or tasks, while FitzGerald et al. [65] developed a taxonomy and speculated as well with regards to future developments.

2014 saw reviews with both increased corpuses as well as conducting more complex classifications and analysis, attempting at conducting reviews that examine more than mere techno-design characteristics or provide initial reports from the field. This is exemplified by the work of Santos et al. [3], which, aside from a classification based on technical, content creation and evaluation aspects, provides the first meta-analysis in order to examine the impact of ARLEs on student performance. Educational benefits were examined in 2014 as well by Radu [66] from the perspective of benefits of AR versus non-AR applications. Bower et al. [44] in their review (which examined how well suited ARLEs are to different pedagogical approaches) for the first time raise the issue of the assistance to the educator and the need to better support them – a topic which they indicate needs further study. Similarly, Sheehy et al. [39] examine whether certain AR approaches impair, support, extend or transform learning according to a self-developed affordances framework. This is also examined by Bacca et al. [67] in their work which focuses on uses, purposes and, importantly, the advantages and limitations of ARLEs.

The question of educational benefits – whether or not ARLEs provide them and in which contexts and under what conditions - continued to be a key topic in following years as well, as can be examined from the 2015 work by Diegman et al.[68] and, ultimately, by the author and collaborators [21], as explored further in this thesis.

More recent reviews, such as by Fotaris et al. in 2017 [69] as well as Sommerauer & Muller in 2018 [15] and Arici et al. in 2019 [70] have focused the intersection between ARLEs and gamification and on reviewing research efforts into students' knowledge acquisition and achievement, respectively. Garzon et al. in 2020 [71] analyse the effect of pedagogical approaches in ARLEs.

One of the most comprehensive recent review works is by Avila-Garzon et al. from 2021 [72] which focuses on bibliometrics, but also reinforces through that lens the work of Fotaris, Pellas et al. [13], [69] in that gamification research of ARLEs is gaining in prominence.

For completeness, it should be noted that there was as well a number of device-specific reviews, including Dunleavy and Dede's review [73] of mobile device-based ARLEs in formal and semi-formal/informal learning environments, Prieto et al.'s work [74] examining orchestration load with ARLEs based on augmenting paper-based artefacts and Avouris and Yiannoutsou's examination [75] of location-based AR games, with a focus on their narrative, interaction modes and use of physical space. Additionally, recently there has been clustering observed in higher education and STEM-focused ARLE research, as analysed in the review works of the Sırakayas in 2020 [76], Theodoropoulos and Lepouras in 2021 [77], Mystakidis et al. in 2021 [78] and Avila-Garzon et al. in 2021 [72].

2.4. Learning analytics background

Pivoting to the question of learning analytics, a definitional approach is needed first. Learning analytics, as refined in conceptualization by Gašević et al. [40], [41], are to be used to make sense of the vast amounts of data about learning collected by the extensive use of technology. To make sense, any learning analytics approach must therefore consider holistically three aspects – theory, design, and data science.

It is a multidisciplinary field, defined by its professional association (Society for Learning Analytics Research - SoLAR) as "the measurement, collection, analysis and reporting of data about learners and their contexts, for purposes of understanding and optimizing learning and the environments in which it occurs" [79]. Thus, it comprises both research and practice, differing from traditional educational data collection in focus on both longitudinal data collection (i.e., observing multiple lessons / student interactions generating data over time) as well as collecting a large number of data points in authentic settings [80]. It tries to collect this data and analyse it via multiple techniques, utilized in diverse areas such as educational data mining [81], statistics, social network analysis, process mining, and text analysis [40].

Some of the areas of interest for this thesis to which learning analytics have been applied include student retention [82] and learning outcomes [83] as well as analysis of emotional affect [84], areas very close to engagement analysis that is the focus of this thesis. In particular, D'Mello, in his analysis of emotional learning analytics [84], highlights that learning is not a cold intellectual pursuit, but is in fact subject to emotional affect, something very well known in engagement theory [20]. D'Mello's work focuses then on technological means to automatically measure, collect and analyse such emotional affect through analysis of multiple sources of emotional affect data, including click-stream data, interaction patterns, bodily signals in order to be applied to multiple areas of interest in learning technologies, including classroom learning analytics, where D'Mello posits the need for camera tracking of students, exposing an expectation that in the future computer vision techniques would be applied to automatically generate the necessary data sets for learning analytics. Importantly, there is a recognition in the work that, although collection of digital data (such as logs or click-stream data) allows for a partial view, even in traditional Technology Enhanced Learning, it is not enough to analyse the learning experience, and a view of the student in their authentic environment and of their actions and affective states is needed. This is, of course, even more highlighted as a need in an environment where the lesson is not purely virtual, but incorporates both real and virtual-world elements, such as an ARLE, where a need for videorecording in order to capture the full scope of actions has been previously highlighted in literature [85].

Turning back to the theory, Gašević et al. work [40] builds on top of previous learning analytics models proposed by Chatti et al. [86] and Greller and Drachsler [87], as well as related process and quality models proposed by Steiner et al. [88] and Scheffel et al. [89]. In their work, however, they posit that the previous models focus too much on operationalization and not sufficiently on base principles. Thus, they posit that any learning analytics activity must focus on three core considerations – theory, design, and data science. All three must be sufficiently considered and requirements fulfilled for the analytics to have meaningful and applicable results.

In terms of theory, Gašević et al. [40], building on previous work [80], [90]–[92], posit that attempting to analyse large data sets without an underlying theoretical basis leads to detection of many associations which in reality are not meaningful. It is the purpose of theory to therefore inform such analysis, identify the meaningful associations (and identify if they even make sense) and develop them into hypotheses built into the analytical model to be tested further in future research. Importantly as well, theory informs what contextual data needs to be collected to allow for a holistic view of the learning experience, a critical concern [93], [94]. They as well note that it is important to recognise that relevant theory for learning analytics does not come just from design and data science, but as well from the theoretical bases for learning, teaching and education.

In terms of the design, three areas of concern are noted [40] - interaction and visualisation design, learning design and study design. In their analysis of interaction and visualisation design, they focus on use of visualization to inform students and teachers of learning progress to support self-regulation of learning, where they note that self-regulation of learning can often prove to be false if not based on appropriate theory but based on only an expectation that visualisation will promote desirable learning. I.e., the student must be interested or intrigued with what information is being visualised to him and be able to utilize it to self-regulate learning – if the information presented, due to not being based on appropriate theory, is not actionable or not relevant to the student, self-regulation will not be acted upon.

In terms of learning design, Gašević et al. [40] point to the same issue as identified by Cuendet et al. [7] , namely that non-integrated techniques and tools such as learning analytics and AR have a detrimental effect, as without an objective-based integration into the learning design, they can point teachers and students to irrelevant findings [94] and increase orchestration load [7], respectively. Therefore, the choice of variables to observe in learning analytics should be guided by decisions, objectives and tasks made in learning design [95], and be connected to tasks given to learners, the tools in use as well as collaborations envisioned with regards to purposes of the data collection [96].

As to study design, Gašević et al. [40] recommend that the design of any studies must take into account understanding of the nature of data collection, possible ways of data analysis, and the type of questions to be answered. Here, DBR [11] approaches are recommended as a natural fit for learning analytics [80], where each intervention is used to further validate the theory underpinning the study and the practical solutions (i.e. research tools) improved with each iteration, utilizing learning analytics approaches to support those activities, with, importantly, taking into account the context, that is based on theoretical bases.

Finally, data science considerations must be taken into account. Compared to most traditional learning research, which focuses on limited datasets arrived at through self-report instruments which are carefully developed taking into account applicable theory and psychometrics and validated via internal consistency, test-retest, construct and predictive validity tests, learning analytics focuses on collection of large amounts of data of specific features [40], such as click-streams, transcripts, eye gazing [40] or, indeed, video [84], which are analysed for indicators of learning processes, outcomes, or activities [40]. Here, it is noted, on the basis of [97], that derived indicators (i.e. those comparing a student or students against the wider class or classes) are found to offer more actionable insight than those based on raw results (i.e. numbers of occurrences for a specific action). When linking the data science considerations to theory and design considerations, data science methods must be adapted to recognise that learning systems are complex, which makes them unsuitable to simplistic general regression models [80], instead requiring more complex analysis that takes into account multiple dimensions of relevance, including those from theory and design and the context of the learning activity being examined [40].

2.5. What is engagement and why is it a useful measure for Technology Enhanced Learning (TEL), including ARLEs?

When identifying appropriate theoretical bases for analysis, as espoused by learning analytics theory presented in the previous section, for ARLEs one quickly identifies engagement as a very important one, explored as such by multiple authors [3], [5], [12], [16], [17], [48], [54], [66].

Engagement in education is defined in a multifaceted way, covering student engagement with the school and the schooling process, through different behavioural, emotional (affective) and cognitive manifestations [20], [98]. In terms of scoping, there is not yet a commonly accepted definition of engagement [99]; it can be observed at both a global, schooling-in-general level (engagement with academics in general), as well as at the level of classroom or individual lesson [19]. In the theoretical examination, it is also still an open question if engagement should be examined as an outcome by itself or as a process leading to an outcome, or both [18]. Some examples of engagement include participation in school activities, attachment to teachers and peers and commitment to classwork and schoolwork in general [98]. Multiple classifications of engagement types exist, usually covering the same overall scope but with different categorisations within it. This thesis adopts the classification of engagement proposed by Fredricks et al. [19], [20] consisting of the following types of engagement:

- *Behavioural* engagement consists of engagement where the student actively participates (i.e., shows interest in the activity and takes physical actions in line with activity design) in academic, social, or extracurricular activities.

- *Emotional* engagement occurs when the student displays an openness to interaction with teachers and classmates, is willing to collaborate with classmates and ask questions of the teacher, as well as showing attachment and openness to academics and schooling overall.
- *Cognitive* engagement is the engagement of the mind of the student – a willingness to work on comprehending complex ideas or put in the effort to master difficult skills, as well as acting in a systematic, thorough fashion when executing school tasks.

One student action can be indicative of multiple types of engagements – for example, asking the teacher for help, listening to their advice, and trying to apply it to solve an issue is indicative of both emotional (openness to ask the teacher for help, listening to them) and cognitive engagement (desire to understand the issue and master it, integrating the given advice and applying it to solve the issue). It should be noted that, especially with observational engagement instruments, there is also often a categorisation of actions which show non-engagement i.e., actions which indicate disengagement from school tasks (doodling on the table, stopping work on the assigned task, etc.), being disruptive (off-topic chatting, disturbing other students, etc.) or other inappropriate and/or off-task actions [100], [101].

When examining Technology Enhanced Learning (TEL) interventions, engagement is therefore a useful measure in its lesson-to-classroom scope, examining it as an outcome which is used as a proxy measure for academic achievement potential, due to findings of positive correlation of engagement with academic achievement and lower drop-out rates, making it a predictor of subsequent academic achievement and success in school [18]. A natural question poses itself, however – why use a proxy measure rather than examining academic achievement directly?

This is in fact necessary in situations where more direct measurement of academic results is not possible. As an example, in the instant case examined in this thesis, this is due to the experiments occurring in the setting of early primary school (1^{st} and 2^{nd} grades, student ages from 6 – 8 years old). In those grades, in the Croatian education system, while grades are assigned (it should be noted that in many education systems, grades are not assigned at those ages) to acclimate students to grading and school discipline, by self-admission of the teachers, students are graded in a motivational or goal-based fashion, rather than as an objective indicator of the attained knowledge and competencies. I.e., in those grades, severe "grade inflation" exists, where most students hold a grade of 5 (A-equivalent), thus making grades not useful as an indicator of academic achievement, requiring a proxy measure, such as engagement.

Specific to ARLEs, engagement has been noted as important and explored previously in literature [5], [48], [54], [66], in an approach that focuses on engagement issues specific to the study in question, with no global conclusions being possible to draw due to the inability to isolate the AR aspect as an experimental variable, a need identified as well in literature [3], [12]–[17].

2.6. The link between engagement and learning analytics

Engagement analysis has been conducted utilizing different instruments, from student and teacher self-reports and focus groups, log analysis to observational instruments [19]. This also includes utilization of learning analytics tools for engagement analysis.

For example, Tempelaar et al. [102] utilized in 2020 learning analytics approaches in order to analyse digital traces for behavioural traces of engagement. Khosravi and Cooper [103] utilized in 2017 learning analytics approaches in order to identify student engagement groupings, in order to support different groups of students (differentiated by engagement) with tailored learning support. Cassano et al. [104] in 2019 combined gamification with learning analytics in order to try to analyse and improve engagement amongst e-learning students. It should be noted that due to the digital nature of e-learning, it is an area most susceptible for learning analytics interventions, with numerous works in the area. Coming back to examples of innovative approaches to utilization of learning analytics for engagement improvement, Sivola et al. [105] in 2021 tried to analyse student needs for learning analytics in the context of engagement by querying pre-service teachers on how learning analytics could support their engagement.

To be noted, however, is that there is limited work in the field with observational analysis, where video-recordings, as an observational approach, are used as input for learning analytics. This has so far been found in the proposal by D’Mello [84] as well as in the work of Worsley [106] who used learning analytics approaches to analyse additional sensor data in parallel to video coding in order to analyse disengagement effects.

3. SPECIFIC METRICS FOR TECHNO-PEDAGOGICAL MATURITY OF LEARNING WITH AUGMENTED REALITY

3.1. Building theoretical considerations through critical review

In attempting to fill the gap identified in the previous section regarding how to review ARLEs and evaluate their maturity in terms of techno-pedagogical affordances as (a part of) an educational support system, the first question being raised is of the approach to determining the relevant theoretical considerations for establishing the review rubric.

Answering that question, in [21] the author and collaborators adopted the critical review approach, based on reasoning by analogy on the basis of Frohberg et al.'s 2009 review of the state of Mobile Learning at the end of 2007 [107]. In that work, the authors argue that when different studies use incompatible models of empirical data, unsuitable for integration, and therefore preventing meta-analysis, a review model needs to be developed. They argue that the incompatibility of models is typical for fields in pre-maturity, which was indeed the case in 2015 when [21] was developed. By utilizing the review model, comparative analysis, and integration of existing considerations from works in the field can be made, to identify patterns and gaps.

To fill the identified gap in existing reviews, it was therefore necessary to design a rubric to allow review of ARLEs on a high techno-pedagogical level. This was done (as published in [21]) by integrating the considerations of two ARLE-relevant educational design principle frameworks to develop the STAR-ARLE review rubric presented below.

3.2. Student and Teacher-relevant considerations' Assessment Rubric for Augmented Reality Learning Experiences (STAR-ARLE)

The *Student and Teacher-relevant considerations' Assessment Rubric for Augmented Reality Learning Experiences (STAR-ARLE)* was developed based on the two relevant frameworks, to address the differing stakeholder considerations - the *Meaningful Learning with ICT* (taking into account primarily student-focused considerations) and the *Orchestration Load reduction framework* (taking into account primarily teacher-focused considerations). Fig. 3.1 provides a high-level overview of the integration of involved frameworks.

In essence, the STAR-ARLE rubric provides for analysis of ARLEs through establishing their maturity over 9 dimensions, four of which are related to making learning meaningful to students and 5 are relevant to the orchestration load teachers experience during lesson execution. These two viewpoints were chosen as they allow for high-level techno-pedagogical analysis, where the technological concerns are blended with their pedagogical impact in a way that is technology-agnostic, as well as being tailored to the concerns of stakeholders.

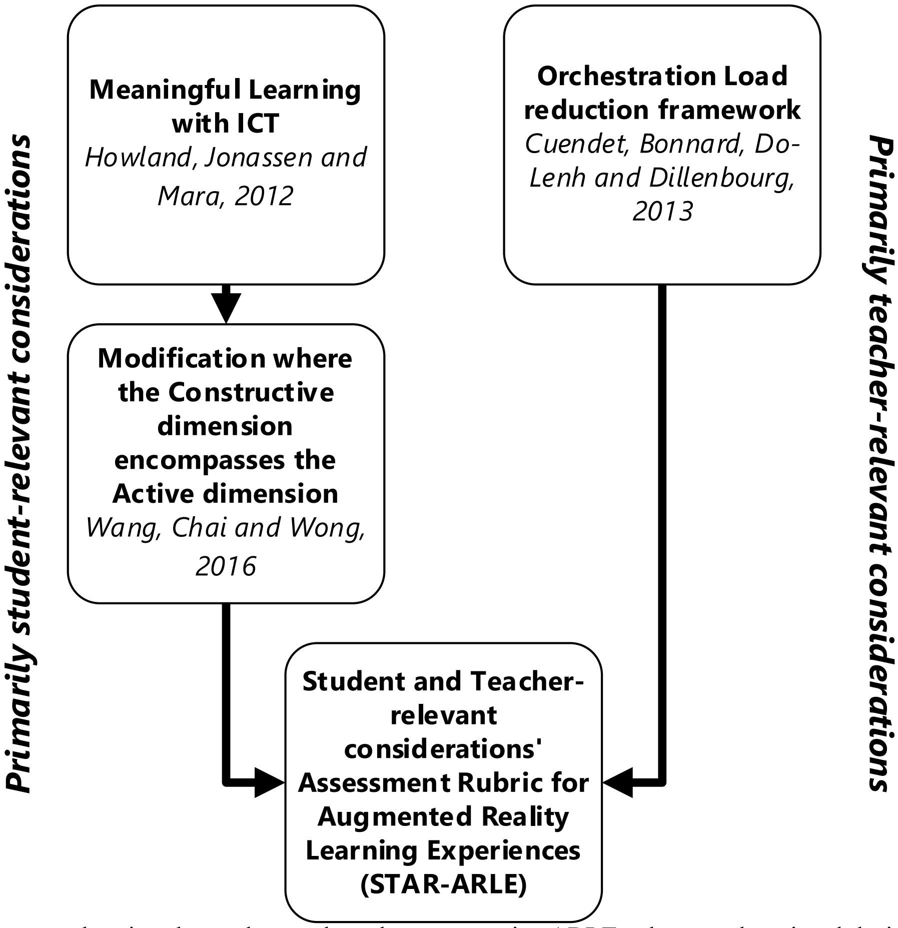

Fig. 3.1. Diagram showing the student and teacher-perspective ARLE-relevant educational design principal frameworks and their relationship to STAR-ARLE. Originally published in [21].

In particular, the *Meaningful Learning with ICT* framework was developed by Howland, Jonassen and Mara in their 2012 book [22] in order to address the issue they've identified of many technological solutions developed on the basis of ICT for assisting in learning (i.e. part of the TEL field) being focused on the technological aspects while providing poor pedagogical support due to not being meaningful experiences to students. This has been identified as a concern for ARLEs as well in previous works [3], [24]. To support development of meaningful ICT learning solutions, they therefore identify 5 key considerations that any solution should enable to support students in their learning journey:

- Learning should be *active* – through manipulation of learning artefacts and observing the results of said manipulation, the learning becomes more meaningful due to active participation of the learner.
- Learning should be *constructive* – the solution should allow the learner to construct their ideas of the materials through a process of inquiry and reflection, rather than the materials being presented as conclusions to the learner.

- Learning should be *intentional* – the initiative regarding progress through the material, including choosing learning goals and being able to understand the progress, should lie with the learner, or at least it should be something the learner and teacher can analyse together.
- Learning should be *authentic* – the problems presented to learners should have a meaningful context, realistic complexity and be anchored in the real world to provide the learner the ability to contextualize them with their pre-existing real-world knowledge.
- Learning should be *cooperative* – ICT solutions should not isolate learners but should provide capabilities and incentives for interaction and peer cooperation, increasing meaningfulness and fostering learning.

In a further development of the framework, Wang, Chai and Wong argued in 2016 [108] that looking at the *active* and *constructive* considerations separately is effectively a distinction without a difference. They consider that those considerations are closely intertwined, with a solution being *active* meaning that it requires hands-on work, while a solution being *constructive* means that it requires "minds-on" work. From the perspective of constructivist learning, this cannot be easily distinguished – hands-on work requires thought and care (observation and reasoning regarding the results) for the manipulation of learning artefacts to meaningful while a constructive solution must be active (i.e., subject to hands-on manipulation by the learner) to allow for the process of inquiry and reflection. Therefore, they propose to subsume the *active* consideration within the broader *constructive* one. Anything else would be "shallow" constructivism - i.e., awarding students for mindlessly trying hands-on solutions without reflection, which cannot be considered neither meaningful nor constructive.

This is a very pertinent reflection for the field of ARLEs. By their nature, ARLEs are active [73], requiring student input and direction through manipulation (whether that is pointing the camera, moving recognised artefacts or moving the device's location), meaning that within ARLEs an *active-only* consideration does not hold much relevance; it is important to identify if such *active* manipulation leads to meaningful (i.e. *constructive* per the discussion above) learning. For this reason, in their construction of STAR-ARLE [21], the author and collaborators have chosen to use the adapted model which incorporates the *active* consideration within the *constructive* one (see Table 3.1, cell ML1-1 regarding the *transmission* level of *constructive* for elaboration).

With regards to considerations relevant for teachers, as the most relevant framework the *Orchestration Load reduction framework* proposed by Cuendet et al. in 2013 [7]. In their work, building upon earlier principles developed for "AR in learning" [25]–[27], [109]–[111], they consider the issue of orchestration load, that is the issue that applying this kind of technology in the classroom is complex and requires a lot of attention and activity from the teacher (or another facilitator) in order to keep the effort needed to orchestrate the learning experience being enjoyed by the students within the constraints of the classroom (both in terms of teacher capacity and competencies, as well as any other resources or considerations contributing to the constraints). Should the needed efforts exceed those constraints, the usability and meaningfulness of the learning experience rapidly deteriorates as the teacher (or facilitator) is overwhelmed by the orchestration load. Therefore, any affordances that can reduce the needed effort (i.e., the level of orchestration load) are desirable and show heightened maturity of the ARLE. While each classroom has its own constraints, Cuendet et al. [7] identify five principles that affect good classroom practices in any case and therefore can be considered in general as external constraints.

Those are *integration* (each learning experience should be connected with other lessons, experiences and materials teaching the same subject, preceding or following the ARLE, whether or not those other learning artefacts are technological or not), *empowerment* (the teacher should be able to take charge of the ARLE when necessary, rather than being forced to always be in the role of facilitator), *awareness* (the teacher should have as effortless as possible awareness and overview of the progress through the ARLE of all students in the class), *flexibility* (the ARLE solution should be adjustable to the situation in the class at time of execution instead of the real-world situation having to conform to the fixed-function ARLE solution), and *minimalism* (the ARLE should provide only the information necessary for the learner for the context they are in, avoiding confusion and frustration, including extra teacher effort arising out of that, from unnecessary or even useless information). The application of those principles is considered to reduce orchestration load [27], assisting the teacher (or facilitator) in maintaining a level that does not exceed classroom constraints and therefore is beneficial to the techno-pedagogical maturity and usefulness of ARLEs.

While the framework is developed primarily to address orchestration load during ARLEs in classroom settings, it is at a high techno-pedagogical level and therefore generalizable to formal and semi-formal contexts where there is a teacher or similar facilitator present and therefore having to manage the orchestration load. This could be experiences incorporated as part of field work, museum visits and similar. It is not, however, appropriate for experiences which are self-directed in informal or other contexts where there is no active and contemporaneous facilitation occurring. While those situations can also suffer from issues due to orchestration load, considered broadly, and the principles presented here may apply in some cases, as they are occurring typically over much longer periods and with much less teacher-student interaction occurring, they represent a sufficiently different techno-pedagogical context to require other considerations to meet their challenges.

In that vein, it should be noted that the framework does not address other highly relevant considerations that are of high importance to any teacher such as safety, relevance of the ARLE to the curriculum or other managerial constraints as those are case-specific and not easily generalizable. In their work, Cuendet et al. do note [7] that such considerations should be best addressed through iterative design-based processes [11] where teachers have a prominent role and are key active stakeholders in the iterative cycles, with iterations being tested in the classroom.

3.3. The dimensions of STAR-ARLE

To construct STAR-ARLE as a review rubric based on *Meaningful Learning with ICT* and *Orchestration Load reduction* frameworks, the considerations in those frameworks needed to be discretized to turn each of the considerations into a dimension with an ordinal scale by which each reviewed ARLE could be graded. This was done for each consideration, developing a 3-point scale based on the differing maturities of the consideration per the descriptions provided in the framework materials and knowledge of the field.

Typically, the first level represents a lack of affordance for the consideration, where – either deliberately or by omission – but clearly from the available documentation, the ARLE simply did not implement any affordances for the consideration. In other words, the ARLE is not at all mature regarding the consideration. The second level represents the level of affordance maturity where it was considered and developed during ARLE design, but in a limited way that is not fully expressive of the theoretical considerations presented in the source frameworks, representing a state of partial maturity. Finally, the third level of affordance maturity represents a state of affordance where all the techno-pedagogical aspects of the considerations were taken into account and the consideration can be considered fully mature as implemented in the ARLE.

Thus, discretized into dimensions of STAR-ARLE, the considerations and the associated levels are presented in Table 3.1 for dimensions/considerations relating to meaningful learning and in Table 3.2 for dimensions/considerations relating to orchestration load.

TABLE 3.1
STAR-ARLE DIMENSIONS OF MEANINGFUL LEARNING
Adapted from Table 2 in [21]

(Category ID) Dimension	**Scale** 1	2	3
(ML1) Constructive	*Transmission* (ARLE is used for transmission of the subject matter through allowing active manipulation of the point of view but not allowing meaningful interaction with artefacts)	*Reproduction or expression* (ARLE is used to support reproduction of subject matter or convergent or minimally divergent knowledge expression by students)	*Synthesis or reflection* (ARLE used by students to synthesize information and/or articulate their personal reflections of subject matter in the form of verbal, written, visual, conceptual, or product-oriented expressions)
(ML2) Authentic	*No representation of real-world phenomena or problems* (No such phenomena or problems related to the subject matter are presented with the ARLE)	*Presentation of real-world phenomena with optional student investigation* (ARLE is used to present examples of real-world phenomena or problems related to the subject matter, with limited interactivity)	*Real world phenomena as anchor for activity* (The ARLE supports students in investigation and proposing solutions or enabling them to express their personal experiences with the real-world phenomena)
(ML3) Intentional	*No support for diagnosing and fixing learning gaps* (Students cannot use the ARLE to support them in diagnosing, strategizing about or improving their learning gaps of the subject matter)	*Support for diagnosing learning gaps* (Students and/or their teachers can use the ARLE to diagnose learning gaps of the students in either self-diagnosis, peer, or teacher evaluation)	*Support for diagnosing and fixing learning gaps* (Students can use the ARLE to self-diagnose and fix their learning gaps of the subject matter)
(ML4) Cooperative	*No cooperative work* (The ARLE does not have any cooperative techno-pedagogical considerations based on its functionalities or subject matter problem approach; any cooperation arising is unplanned emergent behaviour)	*Cooperative work with convergent or minimally divergent knowledge expression* (Students work together, utilizing the ARLE to be engaged in activities requiring convergent or minimally divergent knowledge expression of the subject matter)	*Cooperative work with significantly or primarily divergent knowledge expression* (Students work together, utilizing the ARLE to engage in activities requiring significantly or primarily divergent knowledge expression of the subject matter)

TABLE 3.2
STAR-ARLE DIMENSIONS OF ORCHESTRATION LOAD
Adapted from Table 3 in [21]

(Category ID) Dimension	**Scale** **1**	**2**	**3**
(OL1) Integration	*No integration with other learning activities* (There is no integration of the ARLE with other learning activities for teaching the target subject matter)	*Simple integration with other learning activities* (As an optional add-on, using as input a result of the previous activity, providing its own aggregate output as basis for further activities, etc.)	*Rich integration with other learning activities* (The ARLE is integrated with other learning activities in a rich and smooth way, taking as input complex data or providing the same for follow-up)
(OL2) Empowerment	*No facilities to guide the activities by the teacher* (There is no design consideration of assisting the teacher)	*Limited facilities for the teacher to influence activities* (Teacher interventions can either be ignored by the students or the teacher has only global ability to influence activities)	*Effective and rich capability for the teacher to guide the activities* (There is an effective and rich capability for the teacher to guide the activities in the ARLE)
(OL3) Awareness	*No systematic awareness of the students' state of the ARLE* (The teacher must check with each student to discover their state)	*Only detailed post-experience information* (There is only detailed post-experience information and no or a simplistic ability to view real-time student progress)	*Effective, real-time, ability to view student progress in detail* (There is an effective, real-time, ability to view each student's progress in detail)
(OL4) Flexibility	*Fixed function ARLE* (The ARLE is fixed function, with no possibility to adapt or be adjusted to changing circumstances)	*Only pre-activity adjustment possible* (Adjustment can only be done before commencing the use of the ARLE by the students)	*Real-time adjustment possible* (There is ability to adapt or adjust the ARLE to changing circumstances in real-time)
(OL5) Minimalism	*Poor, cluttered experience* (The ARLE in general presents unnecessary clutter, data and/or features, resulting in an unnecessarily complex experience)	*Experience with unnecessary features* (Due to technological need, capability gap or ineffective design, there are features present that are unnecessary)	*Effective, minimalist experience* (The ARLE reflects what is needed and there is no unnecessary data and/or features present)

3.4. Applying STAR-ARLE in critical review

To apply the developed STAR-ARLE rubric in a critical review of the field of ARLEs, both to examine its soundness and to allow analysis to identify issues with the techno-pedagogical maturity of the field, the author needed to identify relevant previous research works in the field to form the corpus on which the rubric would be applied.

To do so, inclusion criteria for the corpus needed to be defined. They were defined as follows:

- The paper's *methodology* must be amenable to analysis using the dimensions of STAR-ARLE; this excludes purely technology-focused papers - the paper must present a report of an ARLE experienced by learners in prototype or final form with results presented that allow for analysis of any techno-pedagogical claims.
- The ARLE must have a *teacher or facilitator-present* context; that is, it must be held in a classroom or other teacher or facilitator-led environment with active facilitation.
- The presented study must be based on *authentic participants*; that is, the subjects used in the study must be of the same group for which the ARLE is finally intended to ensure the possibility to accurately analyse the presented techno-pedagogical considerations – for example, if the ARLE is intended for primary school students, the study should not be based on prototype use by teachers or surrogate use by university students.
- The paper should contain *sufficient detail* of the design of the ARLE to assess all dimensions of STAR-ARLE

To find papers suitable for the corpus, the following three-step process was used. First, previous reviews of ARLEs [3], [10], [64], [66]–[68], [73], [74] were examined for references to suitable works. This was done in the sequence presented in Table 3.3. Each referenced work was examined for compliance with inclusion criteria, with a first pass to detect if a study or project is being presented and a second pass to apply fully the criteria. This approach initial corpus construction was chosen as the inclusion criteria for those previous reviews of ARLEs were broadly compatible with the presented inclusion criteria, therefore suggesting that the pass rate of works thus identified should be higher than for works found in general academic material searches, which has borne true as can be seen in Table 3.3, as well as ensuring a generally comprehensive first step.

To ensure the correct scope and applicability of the developed rubric, it was confirmed that it was not sparse by identifying at least one ARLE presented in the first-step corpus for each level of each dimension which conforms to that level of the dimension. This was followed by an inter-rater reliability check done on a representative sample (N=20). The check was performed by a researcher not involved with AR experiments of the SCOLLAm project, ensuring objectivity. The STAR-ARLE rubric was deemed to allow for a high level of agreement between raters due to the procedure resulting in Krippendorff's $\alpha = 0.851$ [112].

Following those checks, as the second and third steps of corpus development, the corpus was expanded with searches in the IEEE Xplore Digital Library and the WOS. The corpus was prepared during drafting of [21], therefore it covers relevant works published until April 2016 (end date of corpus development for [21]). The search strings used were consistent with [3], as the previous most comprehensive review.

TABLE 3.3
OVERVIEW OF SOURCES FOR ARLES INCLUDED IN THE REVIEW
Adapted from Table 1 in [21]

Source	**Total references / results**	**Potential includable ARLEs***	**(Additional**) included ARLEs**
A - Augmented Reality in the Classroom [10]	11	9	3
B - Current status, opportunities and challenges of augmented reality in education [64]	51	38	11
C - Augmented Reality Learning Experiences: Survey of Prototype Design and Evaluation [3]	110	45	7
D - Augmented Reality Teaching and Learning [73]	57	14	3
E - Augmented reality in education: a meta-review and cross-media analysis [66]	51	25	2
F - Augmented Reality Trends in Education: A Systematic Review of Research and Applications [67]	49	25	7
G - Review of Augmented Paper Systems in Education: An Orchestration Perspective [74]	79	9	2
H - Benefits of Augmented Reality in Educational Environments – A Systematic Literature Review [68]	38	15	3
I - IEEE Xplore Digital Library (IEEE)	827	743	13
J – Web of Science (WoS)	586	331	8
Grand Total	**1859**	**1254**	**59**

* References/results that are papers which present in detail a project or study incorporating an ARLE. Any duplicates of papers were removed when identified; the copy first identified per the sequence in the source column being considered the original.
** ARLEs passing inclusion criteria were attributed to the source in which they were first identified in the sequence presented in the source column.

That is, for IEEE Xplore Digital Library, the search string *((“augmented reality”) AND (educat* OR instruct* OR learn* OR teach* OR train*))* was used, while for WOS *(“augmented reality”) AND (educat* OR instruct* OR learn* OR teach* OR train*)* was used. As with previous explored references coming from previous ARLE reviews, papers found through searches were first checked for disclosing an ARLE-based study or project and, if so, were subjected to checks against the full inclusion criteria.

It is to be noted that in Table 3.3, as indicated by the second explanatory note, whenever a paper was found in more than one source, it was only counted towards statistics in Table 3.3 once, in the work it first appeared in per the indicated alphabetic sequencing. As well, other review papers identified in section 2.3 were examined for additional suitable references, but none were found that pass the inclusion criteria. For this reason, those reviews do not appear in Table 3.3.

The final review corpus was therefore 59 papers that presented ARLEs which fully passed the inclusion criteria.

3.5. Summary results of the application of STAR-ARLE

The full results of the application of STAR-ARLE are published in [21]. For the purposes of this thesis, to underline the issues of techno-pedagogical maturity of ARLEs and therefore supporting the need for a rubric such as STAR-ARLE, a summary of the results, with limited examples for each level of each dimension, is reproduced below. In interpreting those results, the definitions of the levels of dimensions from Table 3.1 and Table 3.2 should be kept in mind.

3.5.1. Student-related considerations dimensions

With that in mind, the results are presented starting with the dimensions related to student considerations developed from the *Meaningful Learning with ICT framework*.

In the *constructive* dimension, we can differentiate between the level of *transmission*, where the ARLE allows for adjustment of the viewpoint of the observation of the learning artefact, but little support for actual interactive investigation and reflection by the student (this is often the case with visualisation ARLEs such as *Live Solar System* [8] and AR-enhanced books [53]), the level of *reproduction or expression*, where typically a question and answer module is implemented in the ARLE, allowing for multiple-choice or simple manipulation answers to questions (examples are *AR-Fitness* [113] where students point out correct answers in the AR environment through exercise, as well as the more constructive AR-enhanced books which contain a Q&A component [49]), and finally the level of *synthesis or reflection,* where students synthesize information about the subject matter or develop their own reflections on the basis of the materials (this level is typically present in location-based ARLEs where students investigate multiple locations such as in *Environmental Detectives* [114], where they investigate a virtual toxic spill; it is less present, although not inexistant [7] in other types of ARLEs).

As can be seen from Table 3.4, the majority of ARLEs were at the time of witing of [21] at the second level i.e. having a Q&A module or active equivalent thereof and thus providing reproduction or expression affordances.

TABLE 3.4
DISTRIBUTION OF ARLES IN THE CONSTRUCTIVE DIMENSION (ML1)
Adapted from Table 4 in [21]

Constructive Dimension	**Transmission**	**Reproduction or expression**	**Synthesis or reflection**
Count in included papers	13	29	17
Estimated distribution across ARLE domain*	Minority; concentrated in AR books and simulators	Majority	Minority; concentrated in location-based role-playing ARLEs

* The distribution is estimated based on counted exemplar papers

In the *authentic* dimension, the concern is to anchor student activity in real-world phenomena, making the experience more meaningful through being based on something relatable and understandable. The levels of the *authentic* dimension scale with how representative and how integrated real-world phenomena or problems are in the ARLE.

At the bottom end of the scale there are ARLEs which have *no representation of real-world phenomena or problems*, which use innovative AR technology to present abstract problems such as in *Kaleidoscope* [7] where symmetry is explored.

Next level up are ARLEs which *present real-world phenomena with optional student investigation* i.e., the issue being presented by the ARLE is based in the real world, but the students are the passive (or minimally active) recipients of the information about the phenomenon, not being able to fundamentally engage with it. An example would be the ability to learn about the Fukushima nuclear accident through an ARLE [59] but with little affordances offered to investigate the topic through interaction and reflection within the ARLE itself.

Finally, at the highest level, there are ARLEs which *use real world phenomena to anchor student activities* of investigation, problem-solving and expression of own experiences with the real-world phenomena. For example, students can take a location-based AR-enhanced field trip through Florence [55], later using the ARLE information as basis for their own expressive reports regarding their experiences with the visual arts of Florence.

Per Table 3.5, most ARLEs do rely on presenting real-world phenomena, but only a minority of them do so in a way to spur meaningful authentic student exploration and reflection.

TABLE 3.5
DISTRIBUTION OF ARLES IN THE AUTHENTIC DIMENSION (ML2)
Adapted from Table 5 in [21]

Authentic Dimension	**No representation of real-world phenomena or problems**	**Presentation of real-world phenomena with optional student investigation**	**Real world phenomena as anchor for activity**
Count in included papers	17	31	11
Estimated distribution across ARLE domain*	Minority	Majority	Minority

* The distribution is estimated based on counted exemplar papers

In the *intentional* dimension student initiative and understanding of their progress is put at the forefront. Per constructivist theory, learners should be the ones with the initiative; to do so they must have the capability to decide which learning goals to pursue, understand their progress towards them and be supported in identifying and resolving any gaps.

Therefore, the lowest level of the dimension is represented by ARLEs that have *no support for diagnosing and fixing learning gaps*. This is often the case with simulation systems that are very *active* and visually impressive in the examination of the simulated issue, such as in the *Phases of the moon ARLE* [115], but then do not offer any affordances for the student to identify if they understood the issue correctly and to identify any gaps in their gained knowledge.

A step above are ARLEs which assist in identifying erroneous findings, *supporting diagnosing learning gaps,* but do not scaffold correction of those issues in any way. This is present in, for example, the *EcoMOBILE* [116] ARLE in which students explore AR-enhanced water measurement; when students generate a measure outside of the expected range, they are warned that it is erroneous, but there is no assistance in identifying why or how to fix the issue.

Finally, and ideally, ARLEs should *support diagnosing and fixing learning gaps*. Unfortunately, very few ARLEs do so; a rare example is the previously mentioned *Kaleidoscope* [7] where students draw symmetrical images. The ARLE itself then takes the "original" part of the image and superimposes a computer-generated symmetrical image over the symmetrical image drawn by the student, clearly identifying to the student any issues with their symmetrical image and allowing them to explore how to correct it by comparing against the generated correct image.

As can be seen in Table 3.6, most ARLEs do not offer facilities for diagnosing and fixing learning gaps and out of those which do, those with support and guidance for fixing any learning gaps are few.

TABLE 3.6
DISTRIBUTION OF ARLES IN THE INTENTIONAL DIMENSION (ML3)
Adapted from Table 6 in [21]

Intentional Dimension	**No support for diagnosing and fixing learning gaps**	**Support for diagnosing learning gaps**	**Support for diagnosing and fixing learning gaps**
Count in included papers	40	17	2
Estimated distribution across ARLE domain*	Majority	Minority	Few

* The distribution is estimated based on counted exemplar papers

The final dimension based on *Meaningful learning with ICT* is the *cooperative* dimension, which explores if the ARLE are structured in such a way to foster cooperation and collaboration with peer learners, well accepted positive pedagogical concepts which are therefore considered to lead to more meaningful learning. The way ARLEs implement cooperation can be both via experience design (where students are encouraged to cooperate through groupings in the experience or other incentives, but with there being no technological facilities to assist cooperation) or through digital technological features enabling (or even enforcing) that cooperation. Most ARLEs that do employ cooperative affordances do so by organising the lesson in such a way that students need to collaborate between themselves in the real world (through discussion and information sharing, grouping in the classroom, etc.) rather via technological means.

Focusing on the dimension levels, at the lowest level there are ARLEs which neither foster real-world cooperation nor have any digital features in that regard, with any cooperation being unplanned emergent behaviour (which, for the purposes of classification, is not considered as elevating the ARLE to a higher level as unplanned emergent behaviour does not, per definition, come out of planned design intention – see for example the *Italian Renaissance Art* [54] ARLE where the designers report developing an ARLE intended for individual experiences, but where cooperation between students spontaneously emerges). AR-enhanced books are typical representatives of this level [117].

ARLEs which express a need for students to cooperate to answer simple questions (typically by being groped and each member of the group having part of the information needed to answer the question) are on the second level, it being *cooperative work with convergent knowledge expression.* A pioneering example of such an approach is *Alien Contact!* [48], in which groups of students learn mathematics through a fun context of an alien crash-landing, where each student in the group gets part of information needed to answer questions posed as part of the experience.

Fully cooperative ARLEs are considered those that have *significantly divergent knowledge expression* i.e., those that encourage students to reason collaboratively about what was presented, contributing with their own perspectives to synthesize the group solution. This is typically seen in scenario (role-play) investigative location-based ARLEs, such as the previously mentioned *Sick at South Shore Beach* [4].

Unfortunately, a majority of ARLEs do not possess cooperative affordances, with most of those that do doing so in the convergent fashion (see Table 3.7).

TABLE 3.7
DISTRIBUTION OF ARLES IN THE COOPERATIVE DIMENSION (ML4)
Adapted from Table 7 in [21]

Cooperative Dimension	**No cooperative work**	**Cooperative work with convergent or minimally divergent knowledge expression**	**Cooperative work with significantly or primarily divergent knowledge expression**
Count in included papers	29	21	9
Estimated distribution across ARLE domain*	Majority	Minority	Some

* The distribution is estimated based on counted exemplar papers

3.5.2. Teacher-related considerations dimensions

Turning to the dimensions related to teacher concerns, i.e., related to the orchestration load experienced during the execution of the ARLE and the best practices to reduce it, there are five dimensions to consider.

Firstly, there is the *integration* dimension. It fundamentally examines how integrated the ARLE is with the rest of the (non-AR or AR) learning experiences teaching the same subject matter, with ARLEs that are more integrated, fitting in well with other lessons and easily connecting in their inputs and outputs with the rest of the curriculum reducing orchestration load.

To categorise the level of integration, at the lowest level there are ARLEs with *no integration with other learning activities*. Those are ARLEs typically designed by researchers with little or no teacher input, therefore not fitting in well with the rest of the lessons. An example is *Ecosystems Augmented Reality Learning System (EARLS)* [118] which teaches about ecosystem issues through strenuous physical activity – the activity is the goal due to researchers' worry about the lack of exercise of students, but as it is not linked to other activities regarding the same topic, it has high orchestration load.

Simple integration with other learning activities can be done by having the ARLE be based on the results of previous activities or the ARLE creating the basis for a follow-up activity. An example is the previously mentioned ARLE dealing with the Fukushima nuclear incident [59] where after using the ARLE the students are asked to reason about what they've observed and come up with proposed explanations for phenomena which they then validate in the computer lab by looking up what actually occurred. By having such integration, the overall orchestration load is decreased for the teacher as the topic is organically developed between AR and non-AR activities.

Finally, the most integrated ARLEs are those with *rich integration with other learning activities.* In those cases, the ARLEs are fully intertwined with other learning activities teaching the same subject. An example is the *Kinematics Graph* [119] ARLE in which students use the ARLE to augment videos of kinematics experiments they themselves conducted and filmed, allowing them to overlay such videos with additional digital information, allowing the students to gain deeper understanding than if exploring the issue by themselves through correlating what they have seen during the experiments and later on video with textbooks or other 3rd party information sources.

The majority of ARLEs are not integrated. It is important to note however, that of those that do have integration, a high proportion has rich integrations, as shown in Table 3.8. This indicates that achieving rich integration is not significantly more difficult than simple ones, if proper planning, collaboration with teachers and good design work is done.

TABLE 3.8
DISTRIBUTION OF ARLES IN THE INTEGRATION DIMENSION (OL1)
Adapted from Table 8 in [21]

Integration Dimension	**No integration with other learning activities**	**Simple integration with other learning activities**	**Rich integration with other learning activities**
Count in included papers	36	14	9
Estimated distribution across ARLE domain*	Majority	Minority	Some

* The distribution is estimated based on counted exemplar papers

Secondly, the *empowerment* dimension is examined. Modern constructive pedagogical approaches favour the teacher changing from a lecturer to a facilitator. However, when conducting ARLEs, especially if we are considering primary school contexts, the teacher should be *empowered* to take control of the experience if necessary, such as for example to progress the class to a next step of the experience or to control the experience a student is receiving to adjust it to be appropriate for the student.

Most ARLEs have *no facilities to guide the activities by the teacher*, effectively not considering the teacher as a stakeholder in the experience, with the ARLE being a self-contained experience to be experienced by a student, such as in the *AR-SaBEr* [56] ARLE used to teach electromagnetism.

ARLEs with *limited facilities for the teacher to influence activities* allow teachers, on the other hand, to take charge, but only on a global level (affecting all students) or targeted in a manner that the student can ignore the teacher guidance. Such is the case with the *AR image of a spinning Earth* [111], a classroom-scale AR experience in which two students explore the relationship between the Earth and the Sun, with the rest of the classroom observing. The teacher can affect the experience in this case, but only globally, since not each student is experiencing their own ARLE.

Finally, a few ARLEs have an *effective and rich capability for the teacher to guide the activities*, allowing for individual student experience control as well as global control. *TinkerLamp* [7] is an example – it introduces "keys" (cards with QR codes that are recognised by the system) with which the teacher can control the experience for each student with instructions such as "Allow Simulation" or "Pause Class", effectively controlling the experience the student receives and guiding them towards sections most useful for the maturity level of the specific student.

Table 3.9 documents that this high level is achieved in only a few cases; even at the limited facilities level there are few ARLEs, with essentially almost all ARLEs not giving any facilities to the teacher.

TABLE 3.9
DISTRIBUTION OF ARLES IN THE EMPOWERMENT DIMENSION (OL2)
Adapted from Table 9 in [21]

Empowerment Dimension	**No facilities to guide the activities by the teacher**	**Limited facilities for the teacher to influence activities**	**Effective and rich capability for the teacher to guide the activities**
Count in included papers	51	6	2
Estimated distribution across ARLE domain*	Majority	Few	Few

* The distribution is estimated based on counted exemplar papers

Next, it is important to consider the *awareness* dimension. Here, the main concern is if the teacher has systematic awareness of the state of students' ARLEs. This is an important techno-pedagogical consideration as knowing the current situation during the ARLE has a strong impact on the orchestration load for the teacher – if there is no systematic awareness, that means that the teacher must check in with each student to know their progress or presume progress, clearly requiring additional inefficient efforts and therefore increasing orchestration load.

Thus, the lowest level of this dimension is indeed *no systematic awareness of students' state of the ARLE*. This is common with many types of ARLEs, but especially in ARLEs specializing in exploring a specific subject such as the *Live Solar System* [8] ARLE.

The second level covers ARLEs that do have logging and status information available, but *only as detailed post-experience information.* This does benefit orchestration load, as the teacher can observe and analyse the results of the ARLE use afterwards, allowing teachers to meaningfully follow-up with students. It does not assist the orchestration load during the experience itself. An example is *Models in Engineering Graphics Course* [120].

Finally, ideally when considering awareness, ARLEs should allow for *effective, real-time, ability to view student progress in detail*, assisting the teacher in the orchestration of the experience through allowing to see student progress through the ARLE as well as individual discrepancies in real-time. An example of such an ARLE is *EULER* [121], a system for mobile learning field exercises where the teacher can set up a "command post" in the field from which to monitor in real-time activities of students who spread out in the environment to experience the ARLE and conduct their field work, allowing them to react if an issue is observed, as the system is continuously transferring updates from student clients to the central system.

The majority of ARLEs do not have systematic awareness affordances, as can be seen in Table 3.10. It should be noted that the 3rd level presence is highest in this dimension amongst all the orchestration load dimensions, indicating that, whilst most ARLE designers do not consider this affordance, those that do tend to execute it in a competent fashion, potentially indicating that the difficulty of implementing affordances at second or third level is similar.

TABLE 3.10
DISTRIBUTION OF ARLEs IN THE AWARENESS DIMENSION (OL3)
Adapted from Table 10 in [21]

Awareness Dimension	**No systematic awareness of the students' state of the ARLE**	**Only detailed post-experience information**	**Effective, real-time, ability to view student progress in detail**
Count in included papers	38	9	12
Estimated distribution across ARLE domain*	Majority	Some	Minority

* The distribution is estimated based on counted exemplar papers

The next dimension is *flexibility*. In the real-world, it is not always possible to conduct ARLEs perfectly as imagined; students might get sick, parts of lessons might get pushed back and therefore the ARLE should be adjustable to the circumstances occurring in the classroom. This techno-pedagogical affordance therefore measures the flexibility of the ARLE, allowing for reducing orchestration load for the teacher which otherwise increases due to having to "fight with" the ARLE under imperfect circumstances if it is not adjustable.

ARLEs with the lowest level of affordance are *fixed function ARLEs*. Those do not contain any facilities to adjust the experience to account for curricular, attendance or other concerns at issue in the real-world. Examples are numerous and occur in all ARLE types, including AR-enhanced books [51], game-like ARLEs [61], language learning ARLEs [122], simulation ARLEs [58] and location-based ARLEs [114].

At the second level, ARLEs are classified if they offer affordances where o*nly pre-activity adjustment is possible*. This can be either via availability of an ARLE editor allowing for easy change of the content, by having flexible grouping approaches (if grouping is part of the ARLE) or other affordances that allow for pre-experience adjustment to current practical concerns. An example of an ARLE with easy to use authoring tools is *Snap2learn* [123] while many location-based group investigation ARLEs coming in the second wave of such ARLEs, such as *Grey Anatomy* [124], have flexible grouping affordances.

Finally, and ideally, ARLEs should offer affordances to make *real-time adjustment possible* during the execution of the experience itself to allow them to reduce orchestration load by adapting the ARLE to the ongoing experience context. *Tapacarp* [7] is such an ARLE, enabling control of the experience or assignment of tasks to students via control cards, allowing for tailoring the experience to the constraints of the classroom.

As expected, due to techno-pedagogical complexity, the majority of ARLEs are fixed function, but it is encouraging that several ARLEs have authoring and control tools capable of supporting either pre-activity or real-time adjustments (see Table 3.11).

TABLE 3.11
DISTRIBUTION OF ARLES IN THE FLEXIBILITY DIMENSION (OL4)
Adapted from Table 11 in [21]

Flexibility Dimension	**Fixed function ARLE**	**Only pre-activity adjustment possible**	**Real-time adjustment possible**
Count in included papers	42	10	7
Estimated distribution across ARLE domain*	Majority	Some	Some

* The distribution is estimated based on counted exemplar papers

The final dimension considered is the *minimalism* dimension which focuses on the user experience for both the learner and teacher. Here, the principle of user experience design is applied that the ARLE system should only display relevant and necessary information to the user, as displaying superfluous information or having a cluttered UI causes unnecessary complexity which has a negative impact on orchestration load due to learner confusion, additional requests for teacher assistance to understand the options presented and attendant user support issues. Conversely, a minimalist interface allows the focus to be placed on the content of the ARLE, reducing orchestration load for the teacher.

Many early ARLEs were constrained by their platforms in the pre-modern smartphone era, where in general a *poor and cluttered experience* was to be expected. This is the case with *Alien Contact!* [48], which ran on the Windows Mobile platform. While more modern ARLEs tend to have less issues in this regard through both adhering to evolution in the user experience domain and platform user experience guidelines and consequently achieve higher levels of affordance, there are still those that fall into this level of affordance [125].

The second level of affordance in minimalism is represented by ARLEs which offer a user *experience with unnecessary features*. They are differentiated from the first level by being built by following in general modern minimalist approaches, something ARLEs are well suited to by their nature [3], but in the end having features or characteristics which run counter to that general design approach i.e. "unnecessary features" which cause increased orchestration load. For example, the *Italian Renaissance Art* [54] ARLE utilized a minimalist interface by using markers detectable by the AR app as anchors for presenting information about works overlaid over the real-world image. It has no marker occlusion compensation support, and therefore as soon as marker detection falters or the marker is even slightly obscured the information disappears, leading to confusion for the learner and extra orchestration load for the teacher trying to fix the issue. While allowing for a novel approach to present information, this approach therefore turned out to be an unnecessary feature compared to using markers to trigger information in the app which could then be read without worry about marker occlusion.

Finally, at third level of affordance are ARLEs which implement an *effective minimalist experience.* An effective example in this regard is the symmetry learning *Kaleidoscope* [7].

Examining the overall categorisation in this dimension, as presented in Table 3.12, it can be observed that the majority of ARLEs are attempting, naturally, to have minimalist experiences, but with not fully succeeding being common. A minority of mostly older ARLEs (pre-modern) tend to have the lower level of affordance with poor, cluttered experiences.

TABLE 3.12
DISTRIBUTION OF ARLEs IN THE MINIMALISM DIMENSION (OL5)
Adapted from Table 12 in [21]

Minimalism Dimension	**Poor, cluttered experience**	**Experience with unnecessary features**	**Effective, minimalist experience**
Count in included papers	13	25	21
Estimated distribution across ARLE domain*	Minority	Majority	Minority

* The distribution is estimated based on counted exemplar papers

3.5.3. Correlation analysis

In order to explore the relationships between the maturity of different dimensions in order to draw conclusions regarding the interrelationships underpinning the overall techno-pedagogical maturity of the field, as analysed with the STAR-ARLE rubric, a correlation analysis utilizing Kendall's τb [126] was done. The results of that analysis are presented in Table 3.13.

TABLE 3.13
CORRELATIONS BETWEEN STAR-ARLE DIMENSIONS
Adapted from Table 13 in [21]

		Constructive	**Authentic**	**Intentional**	**Cooperative**	**Integration**	**Empowerment**	**Awareness**	**Flexibility**	**Minimalism**
Constru-ctive	**CC+**	1.000	.257*	.226	.573**	.106	.109	.301*	.194	-.275*
	Sig.++		.030	.066	.000	.376	.374	.012	.108	.020
Auth-entic	**CC+**		1.000	.107	.240*	.050	-.008	.206	.106	-.249*
	Sig.++			.385	.044	.678	.951	.087	.383	.036
Intent-ional	**CC+**			1.000	-.098	.040	.384**	.427**	.119	.004
	Sig.++				.427	.746	.003	.001	.341	.972
Coop-erative	**CC+**				1.000	.041	.000	.091	.076	-.155
	Sig.++					.734	1.000	.451	.533	.192
Inte-gration	**CC+**					1.000	.213	.175	.099	-.038
	Sig.++						.086	.147	.414	.752
Empow-erment	**CC+**						1.000	.430**	.349**	.175
	Sig.++							.001	.005	.155
Aware-ness	**CC+**							1.000	.242*	-.059
	Sig.++								.047	.619
Flexi-bility	**CC+**								1.000	-.009
	Sig.++									.944
Mini-malism	**CC+**									1.000
	Sig.++									

All included ARLEs were analysed for correlation (N = 59)
+ Correlation Coefficient
++ Significance (2-tailed)
* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

A full discussion of the correlation findings is presented in [21]; for the purposes of this thesis a summary of key statistically significant findings of both the correlation analysis and the overall STAR-ARLE application is given and discussed in chapter 8.

3.6. Methodological gaps identified via STAR-ARLE review

Examining the works listed in the previous chapter, as well as the corpus of papers selected for analysis and results of the application of STAR-ARLE presented in this chapter, the following methodological gaps can be identified.

Firstly, previously to the author and collaborators work in [21], there existed a gap in systematically examining ARLEs from the perspective of high-level techno-pedagogical considerations through which concerns of classroom stakeholders are addressed. The need for this from a teacher perspective having been previously observed in Bower et al.'s work [44]. From the student perspective, we can observe in previous efforts a split between categorisation approaches [3], [10], [62]–[65] which attempt to document the available technical features or deployed educational approaches on the one hand, and educational benefit analysis on the other [3], [39], [66]–[68], leaving as an open question the *level of techno-pedagogical affordances* to students ARLE designs offer. This is examined to an extent in approach-specific works [73]–[75], but there has not been up to [21] a high level review rubric, that does not depend on the specifics of the approach, general AR approaches (image-based or location based [127]), AR view metaphor (mirror, view-point) instruction or content creation approaches [3], [64], nor especially one that considers the level of techno-pedagogical affordances from all classroom stakeholders' (students' and teachers') perspectives.

Secondly, the (presumably) positive effect on student engagement of ARLEs is a significant question, pondered by multiple researchers in the field [5], [48], [54], [66], due to the previously noted correlation of engagement with academic success and reduced incidence of drop-out [18], [128], especially as there are indications of ARLEs having a positive effect on student motivation and engagement [3], [5], [129]. There is a noted difficulty in determining those effects by the researchers due to there not being much experience in identifying if there are appropriate existing instruments for engagement measurement for ARLEs or what characteristics would a new adopted instrument need to have.

Thirdly, taking into account the author and collaborators' review of ARLEs [21], it can be – and was [3], [12]–[17] - observed that it is difficult to isolate the effect on engagement of ARLEs due to the approaches taken in the research work in the field in the existing literature. Out of the 59 ARLEs examined in [21], 29 had works done examining their effects through quasi-experimental (pre- and post-test) approaches, 13 were experimental, but with the control group having traditional (non-technological) lessons or alternative paper-based materials (5 studies) as control, while 8 were analysed through DBR methodologies [11]. All those approaches, while being able to validate the effectiveness of the individual ARLE, do not allow for a field-wide assessment that isolates the benefit of the AR intervention from the overall benefit of technological intervention i.e., it is not clear if it was the fact that the intervention was AR-based that led to the benefits or the fact that a technological intervention occurred at all, breaking with the traditional classroom experience, which led to the effects, in particular with regards to engagement. That requires an experimental approach that isolates the AR component as the variable. This was attempted in some cases, but unfortunately with either the use of dissimilar content [115], [130] (legacy desktop 2D and 3D animations [115] and internet content on the topic [130] as control group materials, respectively) or through using two different novel technological interventions for the experimental and control groups, without having a baseline [56], [131] (a 3D virtual environment multi-mouse interface [131] and another ARLE [56] used as control, respectively). Due to such controls instead of, for example, a simple multimedia digital lesson with the same content as the ARLE, that would allow for the clear isolation of the AR effects, those efforts also did not allow for an isolation of the benefits of AR.

More recently, work to rectify this gap has been done in limited fashion for early childhood education [17] and university-level education [12], but, aside from the work of the author and collaborators [132], that forms the basis for the exploration in this thesis, there are no studies yet relevant to the primary school education context. This is important to note as primary education (alongside university education) is a focal point of ARLE research [72], [129], [133], making any findings in this context thus very relevant to researchers and practitioners.

4. OBSERVING ENGAGEMENT IN THE CONTEXT OF AR

Based on the background given in chapter 2, as well as findings on gaps presented in the previous chapter, in this chapter an examination is made to identify the appropriate methodology for observing engagement in the context of AR, to isolate the AR use as a variable. This starts with an examination of applicability of approaches for measuring engagement [19] and comparing them against the affordances and practical needs for determining engagement with ARLEs (on the basis of relevant frameworks in previous literature [22], [39]) in an early primary school setting in 1:1 (one tablet per student) scenarios. Finding them not fully appropriate, a new observational instrument for evaluation of engagement in such a context, based on learning analytics approaches, dubbed *Augmented Reality Lessons Engagement Observation* (ARLEO) [134] is proposed in the following chapter, developed considering both previous efforts in the field in terms of engagement observational instruments as well as necessary ARLE affordances in early primary school education. Further in the thesis, the ARLEO instrument is being used for the analysis in chapter 7 of the results of experiments in the application of the model developed in chapter 6. In Fig. 4.1 the elements previously analysed are coloured white, elements analysed in this chapter are highlighted in green, while the elements analysed in the following chapters are shaded with diagonal stripes.

4.1. Applicability of approaches for examining engagement

Per Fredricks et al. [19], in primary and secondary education 21 instruments for evaluating engagement in three different categories can be identified:

- *Student self-reports* are instruments through which students report their own engagement levels via questionnaires, with the questions typically having pre-set answers (for example, Likert-scale answers).
- *Teacher reports* are instruments where teachers evaluate and score student engagement levels on a basis of a form with predefined questions used to elicit systematic information about the specific student's engagement.
- *Observational instruments* are instruments which employ direct observation by trained observers of student and teacher activity during lesson execution, who record their observations and code student engagement on a basis of predetermined coding systems that allow for classification of observed student activity.

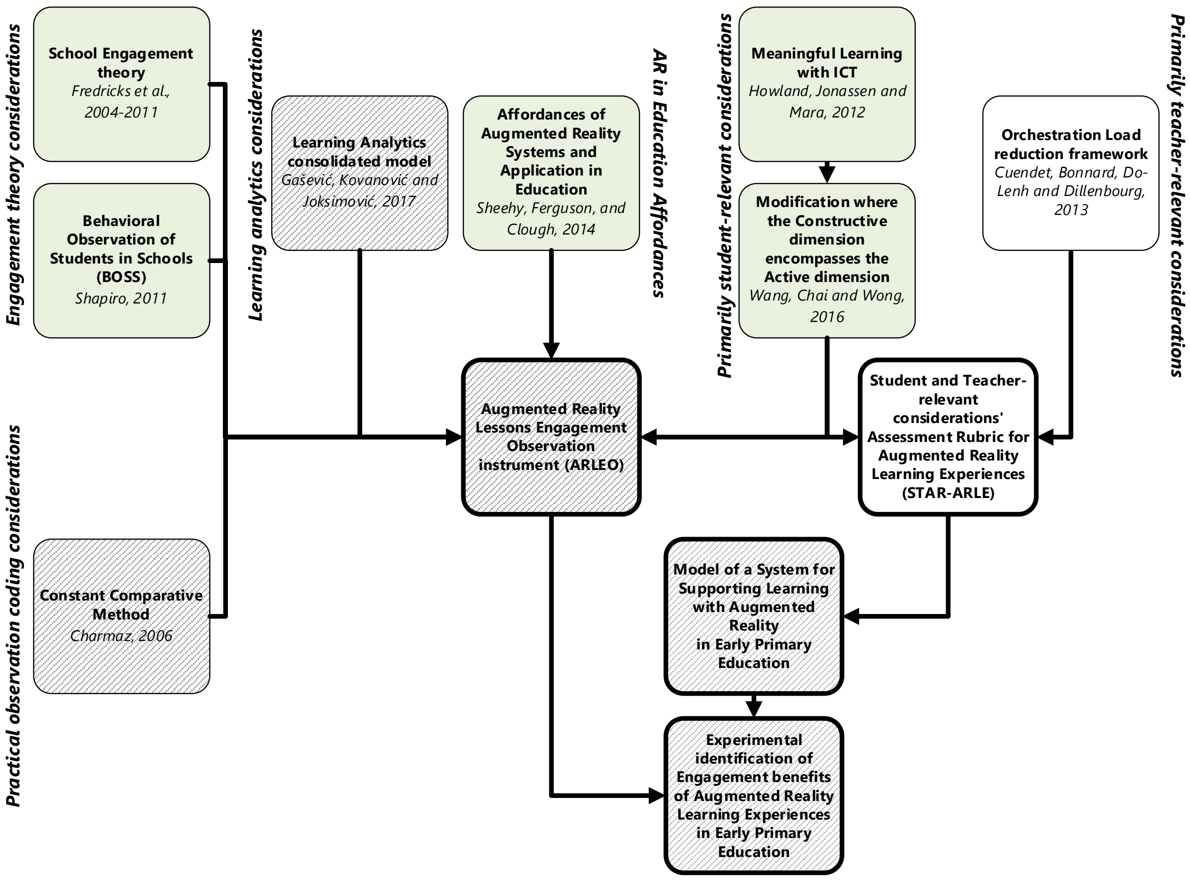

Fig. 4.1. Overview of major theoretical bases and contributions, with highlights for chapter 4. Expanded from Fig. 1 in [21].

Within ARLE research, to understand the student experience, the most common approach for engagement analysis was utilization of student self-reports on the basis of one of the existing instruments or creation of own questionnaires or tests, as well as student focus groups [135]. In early primary school use of ARLEs – an application which is observed to need further engagement exploration in literature [135], [136] – self-reports are not appropriate. Early primary school students lack the maturity to give graduated responses that are needed with Likert-scale answers and lack self-reflection at a level to be able to give a detailed descriptive analysis of their experience. The author came to this conclusion through his own DBR efforts attempting to determine the appropriate approach for evaluating student engagement.

Student self-reports were trialled first during early ARLE DBR cycles in academic year 2015/2016 with first and second grade students (ages 6-8). While students were enthused by the experience of the prototype ARLEs deployed at the time, they had difficulty expressing a nuanced feedback; Likert-style questionnaires, even with simplified language to be more adjusted to the age group, led to extreme polarization of the results, with the majority uncritically selecting strongly agree options, while rare opposition resulted in strongly disagree; students typically responded to all questions in the questionnaire with the same response (either strongly agree or strongly disagree). Following-up, the researchers found confusion - the students did not understand why they were being asked those more detailed questions when they considered the experience either "great" or "they did not like it". A simplified questionnaire with three smiley faces as possible answers (frown face, neutral face, and smiley face) led to similar results. It was therefore concluded that student self-reports would not provide the needed granularity nor trustworthiness of responses to be used for engagement analysis.

Teacher reports were as well determined to not be appropriate for analysis of engagement as, due to the application of 1:1 approaches (one tablet per student), creating personal learning environments, the teachers had difficulty (as would be expected per orchestration load theory [7]) to continuously observe engagement of each student throughout the lesson and remember and report it systematically afterwards, giving at most overall or highly abstracted opinions on student engagement ("they were really enthusiastic today" or "in general it was good, but some had trouble understanding it"), with exception of some typically non-engaged students which showed increased engagement during ARLE use. The teachers also could not differentiate the levels of engagement observed with ARLEs versus other digital lessons deployed as part of SCOLLAm, making the approach not suitable for any comparative analysis.

Finally, it was attempted to use activity logs recorded by the deployed prototype ARLEs as a proxy student self-report. This was found to be deficient due to such logs lacking real-world context – for example, if there are multiple incorrect answers provided by a student followed by the correct one, from the logs it is not clear if the selection of the correct one happened due to consideration of other possibilities after trying and getting the wrong ones (cognitive engagement), after consultation with a peer or teacher (emotional engagement) or through running around the room trying out possible responses at random (behavioural engagement)[1].

Therefore, application of an observational approach was warranted to gather data at a sufficient level of granularity to be able to analyse student engagement during ARLEs in an early primary school setting.

4.2. Comparison of existing observational instruments for engagement

4.2.1. Determination of criteria

To determine if existing observational instruments for engagement are suitable for application in evaluation of ARLEs in early primary school, it is necessary to determine the criteria which such an observational instrument should fulfil. The important aspect in this

[1] An analysis on how to integrate in future work activity log processing into the approach finally chosen is given in section 8.5.3.

consideration is student-related affordances and the ability to measure engagement in the context of them.

For this, two frameworks are applicable. The first is the *Meaningful Learning with ICT* framework developed by Howland, Jonassen and Mara [22], previously presented in section 3.2, referred to in this section by the acronym ML-ICT, which represents an overarching theoretical framework for examining the meaningfulness for students of any TEL approach.

A similar AR-specific classification framework was developed by Sheehy, Ferguson and Clough in their work [39], named the *Affordances of Augmented Reality Systems and Application in Education* (AARS-AE), which considers as essential for educational application of AR the affordances of:

- *Collaboration* meaning that ARLEs should foster student peer cooperative work.
- *Connectivity* meaning that information presented in the ARLE should be able to be connected directly and immediately with the student's surroundings.
- *Student-centeredness* meaning that ARLEs should provide a personalized experience for the student.
- *Community* meaning that students when experiencing the ARLE should experience it in a fashion that relates to the experiences of the other students.
- *Exploration* meaning that ARLEs should enable investigative learning with a safe environment, where students examine problems and explore possible solutions.
- *Shared knowledge* meaning that the student build-up of knowledge should be communal i.e., transferable from one student to the other, rather than each having to construct meaning fully individually.
- *Multi-sensorness* meaning that the ARLE should enhance the sensory experiences of the student in the real world.
- *Authenticity* meaning that the ARLE should reflect real-life skill or practice.

When examining engagement, as opposed to techno-pedagogical maturity, the combination of ML-ICT and AARS-AE is beneficial as it allows addressing of emotional engagement through its focus on affordances such as *community*. This is especially the case as the compatibility of the two frameworks is high – *collaboration* (AARS-AE) and *cooperation* (ML-ICT) are functionally heavily related, while *authenticity* is present in both frameworks. AARS-AE does bring its own considerations to the table with *connectivity*, where it wants to ensure that the ARLE is utilizing information from the student's environment; something that is not considered directly in the more general ML-ICT (it can be considered an aspect of *authenticity* there). *Student-centeredness* (AARS-AE) is a term that encompasses the *active* and *intentional* considerations of ML-ICT in that it expects content personalized for the student which encompasses both the expectation that the student to be the actor of the ARLE rather than a passive recipient, as expected of the *active* consideration of ML-ICT as well as the expectation that the student can set the pace, diagnose their learning gaps and fix them, as expected of the *intentional* consideration of ML-ICT. *Community* and *shared knowledge* considerations of AARS-AE can be connected to the *cooperation* consideration in ML-ICT, but they are both broader terms – cooperation (in the ML-ICT context) focuses on only the direct cooperation between students during the conduct of the lesson in progress, while the community and shared knowledge considerations look at the build-up of results throughout the ARLE that are based on direct cooperation, but also take into account the communal experience aspect and classroom-wide exchanges. Finally, specific to ARLEs are the considerations of *exploration* and *multi-sensorness* of AARS-AE that can be considered as ARLE-specific specializations of the *constructive* consideration of ML-ICT.

For an observational instrument to be suitable, therefore, for examining engagement of ARLEs in early primary school context it should allow that a well-developed ARLE (i.e., one that is in line with the specific considerations of AARS-AE as well as considerations of ML-ICT more generally) can express its full range of affordances and for those affordances to be correctly identified and measured in terms of their impact on student actions and therefore on student engagement. If such full scope of coverage is not possible it can lead to certain aspects of a well-developed ARLE not being evaluated in terms of engagement impact as simply a certain part of the scope is not considered as relevant for the observational instrument, thus causing results that do not correctly measure engagement effects of ARLEs on students in early primary school.

ARLEs not being fully mature from a techno-pedagogical perspective [21], it is also preferred to have an observational instrument which can capture all types of engagement, in order to assist ARLE researchers with their design development, so that later DBR cycles can be informed by theoretically well-based, data-rich findings, providing comprehensive engagement analysis, grounding and informing development targets for further research in later DBR cycles. More practically for the studies covered by this thesis, due to the project set-up of SCOLLAm, any observational instrument should be able to effectively cover 1:1 one tablet per student scenarios occurring in an early primary school setting.

4.2.2. Comparison

In their work, Fredricks et al. [19] identify four observational instruments for engagement:

- The BOSS instrument, or *Behavioral Observation of Students in Schools* [100] is an instrument designed to examine behavioural engagement by observing if individual students are engaged or not through discretization of the whole observation period into 15-second windows for which, for each student, a determination is made on engagement. It is designed to observe active and passive behavioural engagement and considers non-engagement as well.
- *Classroom AIMS* [137] is an observational instrument designed for observing classroom and lesson level teacher practices in order to determine teacher effectiveness. It is based on a 75-item questionnaire to be filled out by the observers, scoring each item with a score between 1 and 3. Amongst those are questions regarding class emotional and behavioural engagement.
- The MS-CISSAR instrument, or *Code for Instructional Structure and Student Academic Response* [101], is a student-level observational instrument which classifies student actions via a 105-event taxonomy, including events which indicate behavioural positive, neutral and negative engagement. It is based on 20-second observational windows for discretization of the observation period.
- The IPI instrument, or *Instructional Practices Inventory* [138], is a classroom and lesson level instrument for engagement evaluation through coding of student-teacher interactions through three-minute observation sessions by trained observers, examining cognitive engagement which can be positive (intrinsic engagement by students), neutral (engagement triggered by teacher instructions) or negative (students not engaged)

The listed instruments are examined against the determined criteria in Table 4.1. In that examination, we conclude that the BOSS instrument represents good potential candidate or at least a basis for the approach to be taken. It supports the needs of observation of 1:1 ARLE use, it is based on observation of individual student actions and supports behavioural engagement observation. It is, however, not a suitable candidate in the end due to not supporting observation of cognitive and emotional engagement making it incompatible with evaluation of affordances for the *community* consideration and partially compatible with the *collaboration/cooperative* and *shared knowledge* considerations.

Similar concerns apply to MS-CISSAR, a similar individual student action observation instrument. In its case, however, the overall compatibility is lower as it disregards considerations of *cooperation/collaboration*, which BOSS considered as possible active (behavioural) engagement.

TABLE 4.1
COMPARISON OF EXISTING OBSERVATIONAL INSTRUMENTS AGAINST AARS-AE, ML-ICT AND PRACTICAL CRITERIA
Adapted from Table 1 in [134]

Criteria	BOSS	Classroom AIMS	MS-CISSAR	IPI
Active (ML-ICT)	*Compatible* (individual student focus)	*Compatible* (classroom focus)	*Compatible* (individual student focus)	*Not compatible* (teacher-student interaction focus)
Constructive (ML-ICT)	*Compatible* (active/passive/off-task engagement of individual student)	*Partially compatible* (classroom focus with overall assessment - difficult to examine)	*Compatible* (individual student focus)	*Not compatible* (teacher-student interaction focus)
Intentional (ML-ICT)	*Compatible* (individual student focus)	*Partially compatible* (classroom focus with overall assessment - difficult to examine)	*Compatible* (individual student focus)	*Not compatible* (teacher-student interaction focus)
Collaboration/Cooperative (AARS-AE & ML-ICT)	*Partially compatible* (can be considered as active engagement but is not targeted)	*Compatible* ("participating in class" item)	*Not compatible* (individual observation only)	*Compatible* (supports collaboration scenarios)
Authenticity (AARS-AE & ML-ICT)	*Not applicable* (lesson design, not engagement evaluation issue)	*Not applicable* (lesson design, not engagement evaluation issue)	*Not applicable* (lesson design, not engagement evaluation issue)	*Not applicable* (lesson design, not engagement evaluation issue)
Connectivity (AARS-AE)	*Compatible* (individual student focus)	*Partially compatible* (classroom focus with overall assessment - difficult to examine)	*Compatible* (individual student focus)	*Not compatible* (teacher-student interaction focus)

Student-centeredness (AARS-AE)	*Compatible* (individual student focus)	*Partially compatible* (classroom focus with overall assessment - difficult to examine)	*Compatible* (individual student focus)	*Not compatible* (teacher-student interaction focus)
Community (AARS-AE)	*Not compatible* (does not consider emotional engagement of students)	*Compatible* ("participating in class" and "expressing excitement" items)	*Not compatible* (does not consider emotional engagement of students)	*Compatible* (supports collaboration scenarios)
Shared Knowledge (AARS-AE)	*Partially compatible* (can be considered as active engagement but is not targeted)	*Compatible* ("participating in class" item)	*Not compatible* (individual observation only)	*Compatible* (supports collaboration scenarios)
Exploration (AARS-AE)	*Compatible* (active/passive/off-task engagement of individual student)	*Compatible* (classroom focus)	*Compatible* (individual student focus)	*Not compatible* (teacher-student interaction focus)
Multi-sensorness (AARS-AE)	*Compatible* (individual student focus)	*Partially compatible* (classroom focus with overall assessment - difficult to examine)	*Compatible* (individual student focus)	*Not compatible* (teacher-student interaction focus)
Types of engagement evaluated	*Behavioural*	*Behavioural Emotional*	*Behavioural*	*Cognitive*
Support for 1:1 approach	*Supported* (individual student focus)	*Supported* (classroom focus)	*Supported* (individual student focus)	*Not compatible* (teacher-student interaction focus)
Duration	*15-second intervals (by default), any length of lesson*	*Lesson duration*	*20-second intervals, any length of lesson*	*Three-minute observation of a class*
Early primary school support	*Supported*	*Supported*	*Supported*	*Supported*

Classroom AIMS is specific in that it is the only observational instrument which was evaluated as being at least partially compatible in all categories, with no categories in which it is incompatible. It supports both behavioural and emotional engagement observation. However, its overall focus, which is on evaluation of teacher performance, makes it unsuitable for a student engagement-focused observation. It also provides for only global lesson-level results, without granularity that would allow for evaluation of the course of the lesson or other analytical approaches opened by having discretized observation periods. As such, if the focus is on evaluating teacher performance during ARLEs it might be suitable (further analysis would be required to decide), however for a student-focused engagement observation it is not suitable.

IPI is designed for generating quick snapshots of the engagement situation, typically in the context of quickly determining engagement throughout the school. It is based on one-off 3-minute observations during a lesson, focusing on teacher-student interactions. As such, it suffers from similar issues as Classroom AIMS as it does not allow for detailed examination of ARLE engagement progression on student level throughout the lesson, especially as ARLEs are developed with a constructivist approach in mind, where the teacher is a facilitator for the experience in which the student is being guided by the AR software. As such, aside from the previously mentioned issues, an instrument focusing on student-teacher interaction is not appropriate.

Taking the above analysis into account, BOSS, while not itself fully aligned with needs of ARLE engagement observation, represents the best basis for development of an ARLE-compatible engagement observational instrument for observing student engagement in early primary school students during 1:1 ARLE experiences. Such an instrument should allow for observation of emotional and cognitive engagement in addition to behavioural one. Care must be taken, however, to address the issue of observation load, as increasing the complexity of observation to account for other types of engagement with a classroom-size of students is likely to overwhelm an observer in real-time observation.

5. ALGORITHMS FOR EXTRACTING LEARNING ENGAGEMENT IN ACTIVITIES WITH AUGMENTED REALITY IN PRIMARY SCHOOL SETTINGS BASED ON LEARNING ANALYTICS PRINCIPLES

Based on the above-presented considerations, in this chapter the development of the *Augmented Reality Lessons Engagement Observation* instrument or ARLEO is presented.

In Fig. 5.1 the overview of applicable theory for developing ARLEO is presented. As previously explored, consideration of AARS-AE and ML-ICT-derived affordances (shaded in yellow in Fig. 5.1) is important as the base for methodology development for ARLEO. In Fig. 5.1, the other theoretical bases, previously explored and further developed in this chapter, are highlighted in green. This includes learning analytics theory [40], as ARLEO is based on constructed algorithms based on learning analytics as applied to video records processing, which is at the heart of ARLEO's methodological approach. Further consideration is given to engagement theory [19], [20], [100] and practical considerations for coding observations [139], as key bases and methodological concerns for ARLEO. ARLEO is used in the following chapters for the identification of engagement benefits of ARLEs in early primary education based on the model of a system for supporting learning with ARLEs (shaded in Fig. 5.1).

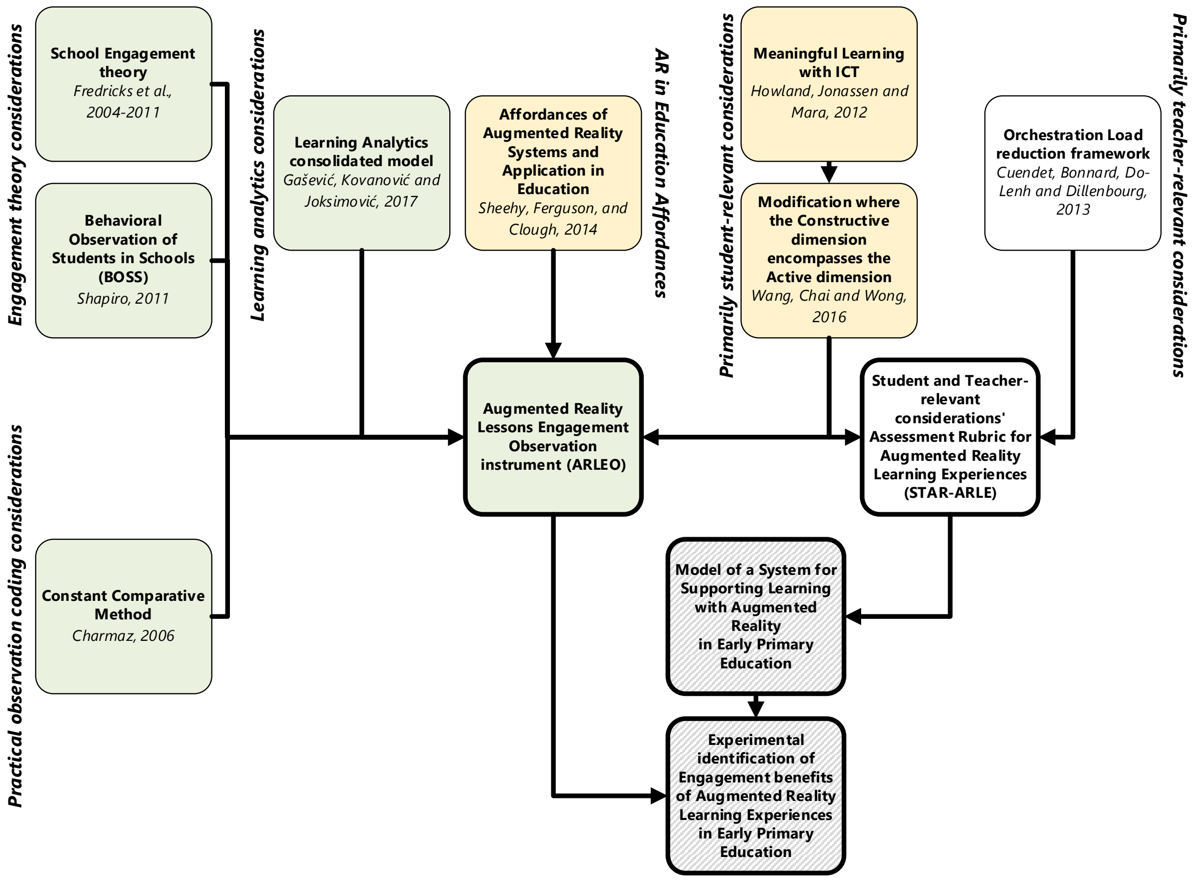

Fig. 5.1. Overview of major theoretical bases of ARLEO, with ch. 5 highlights. Expanded from Fig. 1 in [21].

5.1. Application of learning analytics to development of an ARLE engagement observational instrument

Applied to the consideration of development of an ARLE engagement observational instrument, learning analytics theory, as explored in section 2.4, posits that any such instrument must be grounded in valid theory, in this case with regards to engagement and the categories thereof, as described in the previous chapters (including the best practice of creating non-engagement categories, indicating a lack of engagement, as well as aggregate engagement categories, indicating at least one positive type of engagement being observed, as observed in BOSS and MS-CISSAR). Relevant design considerations must be considered from a learning design perspective, which in this case means taking into account the scope of considerations arising from the relevant techno-pedagogical affordances frameworks such as AARS-AE and ML-ICT. Finally, it is important to create a situation where data science principles can be applied, for which, observing the approaches taken with existing engagement observation instruments, it is necessary to create a rich data environment, which requires application of the discretized student-specific periodic observational approach (segmentation being a well-known analytical problem in learning sciences [140]), creating a nuanced and granular view of student engagement across the engagement categories during the lesson.

With the coding of multiple categories, the issue of overwhelming the observer must be addressed. For this purpose, as a departure from BOSS and MS-CISSAR, while embracing technological progress which allows for cheap and easy utilization of video equipment, ARLEO proposes replacement of the real-time observer-coders with video-recording the progress of ARLEs, allowing for later individual coding of each student's actions during the discretized periods, achieving a much higher granularity, precision, and detail of information as required by learning analytics, through being able to observe each student's actions in detail, following his or her progress from the beginning of the lesson, through the ARLE use to the end, while being able to stop, rewind and analyse in detail any action which is not clear in terms of coding in the first pass. The need for video-recording of ARLE use in order to be able to analyse student activity in detail has basis in previous literature [85], as when observing an activity where a classroom full of students is conducting constructivist learning guided each by their own device, it is difficult to make detailed analysis or logs of actions from the observer perspective in real-time due to overload.

Practically, when tried, it has been observed that videorecording with one camera from a fixed vantage point does not give sufficient visibility into student actions as often there can be obscuring of important activity of a student in the background by a student more in the foreground, especially if the students are required to move about the classroom due to ARLE design. With two cameras set-up in such that there is crossover of vantage positions in the centre of the activity area (as shown on top of Fig. 5.2), the issue is highly mitigated, with only rarely there being a situation where a student cannot be properly observed in their activity from at least one vantage point. For this reason, ARLEO is recommended to be used with a dual-camera set-up as the video-recording basis of input for coding.

A final theoretical consideration is the question of the approach to coding student actions to allow for a meaningful interpretation of results. BOSS and MS-CISSAR utilize predefined, fixed coding catalogues with descriptions of each student actions and associated interpretations. Those catalogues are developed with traditional lesson design in mind (i.e., teacher-led learning in a traditional paper-based classroom environment using textbooks) and are therefore not suited to a modern TEL environment where each ARLE might elicit different student actions, some of which cannot be coded in line with entries in thusly defined catalogues. As each ARLE might elicit different actions depending on its design, especially as it is a field still not reached full maturity and still experimenting with its design approaches [21], a fixed catalogue is inappropriate and an approach to development of a dynamic catalogue which keeps in mind its ultimate purpose (i.e. determination of student engagement of different types) is needed. In ARLEO, the constant comparative method developed by Charmaz [139] is used for this purpose, where through analysis in multiple steps, student actions are coded into categories (i.e. catalogue entries) through coding into more and more abstract concepts through comparison of data with data, data with category, category with category and category with concept. From this method ARLEO inherits its first three stages of coding in the algorithm described below: initial coding, focused coding, and axial coding. The fourth stage described by the constant comparative method, theoretical coding, is not utilized as not applicable; instead, period coding is used to align coded student actions with discretized periods as seen with BOSS and MS-CISSAR to allow for analytics of student engagement for each student throughout the lesson.

5.2. ARLEO observational instrument process flow and algorithms

With those considerations taken into account, this section defines the process flow for determining student engagement during ARLE lessons, comprising multiple algorithmic steps, as summarized in Fig. 5.2.

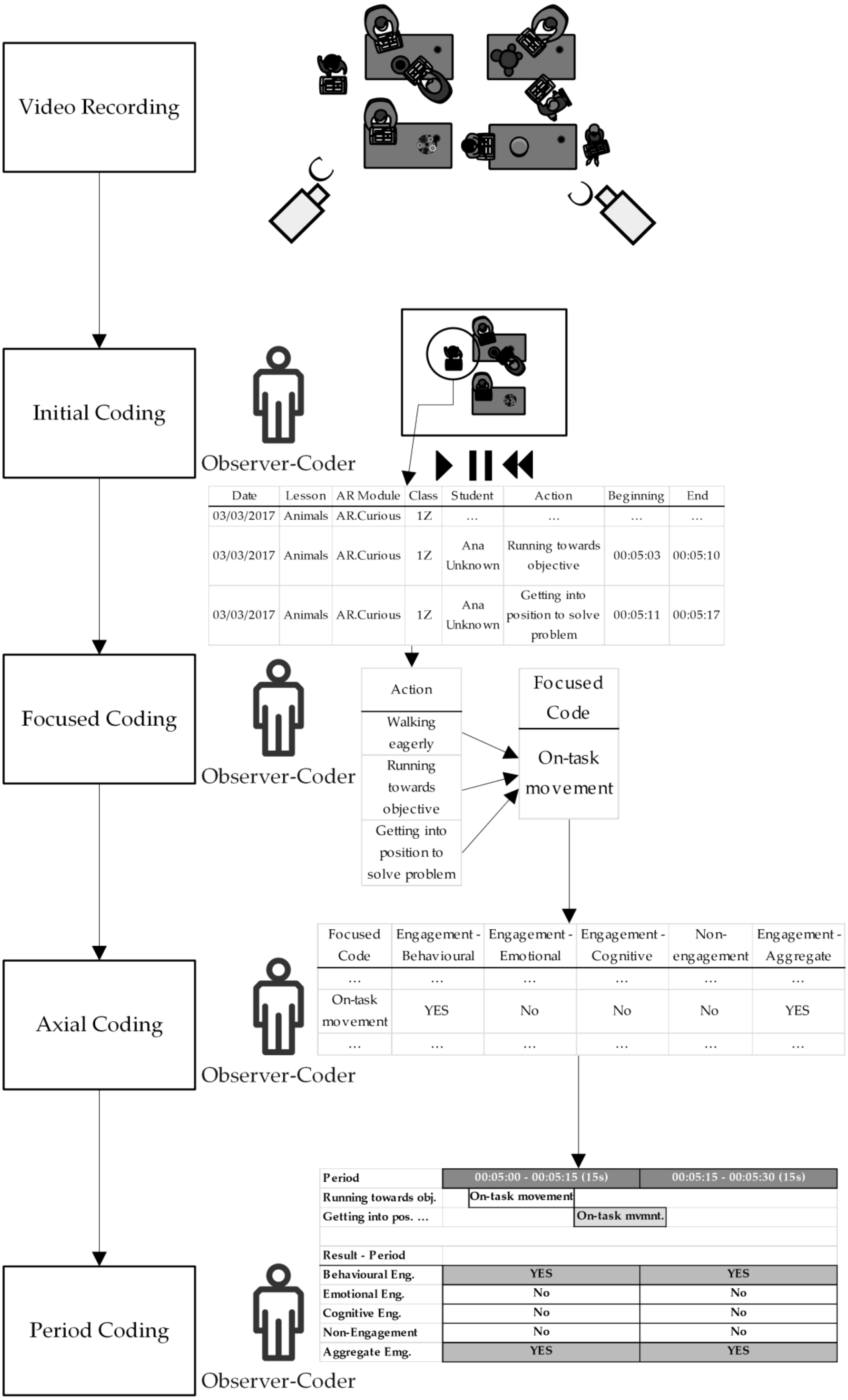

Fig. 5.2 ARLEO coding example. Originally presented in [134].

The step-by-step process flow is:

1. *Video recording* – a video recording of the lesson where an ARLE or other TEL intervention is being performed is to be taken, ensuring that the video captures such viewpoints to allow clear observation of each student's action throughout the lesson. This typically requires two cameras set up in cross-overlapping fashion (Fig. 5.2), identified for below algorithm definition purposes as $C_{\mathcal{L}}$ and $C_{\mathcal{R}}$.
2. *Initial coding* – determining the blocks of raw data and their properties and dimensions [139] – for each student S_i a set of actions $\mathcal{A}_{si}$ is observed, where $\mathcal{A}_{si} \in \mathcal{A}$, which is the set of all student actions coded. Every student action $\mathcal{A}_{si}$ observed is comprised of the following coding attributes $\mathcal{A}_{si} = \{\mathcal{L}_k, C_{\mathcal{L}k}, \mathcal{DT}_{\mathcal{L}k}, S_i, \mathcal{DES}_{\mathcal{A}si}, \mathcal{T}_{\mathcal{A}sib}, \mathcal{T}_{\mathcal{A}sie}\}$ denoted with the following:
    a. Lesson $\mathcal{L}_k \in \mathcal{L}$ being observed, where $\mathcal{L}$ represents the set of all lessons recorded
    b. Class $C_{\mathcal{L}k} \in C$ being observed during the lesson $\mathcal{L}_k$, where C represents all classes in the experiment
    c. Date of the lesson $\mathcal{DT}_{\mathcal{L}k}$,
    d. Identifier of the student who performed the action in a lesson $S_i \in S_{\mathcal{L}k} \in S$ where S represents the set of all students in the experiment, and $\mathcal{L}_k$ a lesson.
    e. Description of the action (free form) $\mathcal{DES}_{\mathcal{A}si}$,
    f. Normalized beginning and ending time codes of the lesson $\mathcal{L}_k$ (in seconds) $\mathcal{T}_{\mathcal{L}k} = \{\mathcal{T}_{\mathcal{L}kb}, \mathcal{T}_{\mathcal{L}ke}\}$ - normalized meaning presented as offsets from the determined absolute beginning of the lesson in the recordings.
    g. Normalized beginning and ending time codes of the action (in seconds) $\mathcal{T}_{\mathcal{A}si} = \{\mathcal{T}_{\mathcal{A}sib}, \mathcal{T}_{\mathcal{A}sie}\}$ - normalized meaning presented as offsets from the determined absolute beginning of the lesson in the recordings.

    The process of the initial coding can be described with if (end of an action $\mathcal{A}_O$ is observed in $\mathcal{V}_{\mathcal{L}xCrTo}$) $\wedge$ ($\mathcal{A}_O \notin \mathcal{A}_{\mathcal{L}x}$)

    $\mathcal{L}_{\mathcal{A}o} = \mathcal{L}_X$, $C_{\mathcal{A}o} = C_{\mathcal{L}x}$, $\mathcal{DT}_{\mathcal{A}o} = \mathcal{DT}_{\mathcal{L}x}$, $S_{\mathcal{A}o} = S_O$,

    $\mathcal{DES}_{\mathcal{A}o}$ = observer-coder provided description,

    $\mathcal{T}_{\mathcal{A}ob}$ = check back in $\mathcal{V}_{\mathcal{L}x}$ and determine beginning of action (first in $\mathcal{V}_{\mathcal{L}xCrTo}$ and if not found in $\mathcal{V}_{\mathcal{L}xClTo}$)

$\mathcal{T}_{\mathcal{A}oe} = \mathcal{T}_O$

$\mathcal{A}_O = \{ \mathcal{L}_{\mathcal{A}o}, C_{\mathcal{A}o}, \mathcal{DT}_{\mathcal{A}o}, S_O, \mathcal{DES}_{\mathcal{A}so}, \mathcal{T}_{\mathcal{A}ob}, \mathcal{T}_{\mathcal{A}oe} \}$

$\mathcal{A}_{\mathcal{L}x} = \mathcal{A}_{\mathcal{L}x} \cup \{\mathcal{A}_O\}$

Algorithm 5.1 for a specific lesson $\mathcal{L}_X$ part of the overall lessons of the study $\mathcal{L}_X \in \mathcal{L}_S$, where $\mathcal{A}_{\mathcal{L}x}$ represents the set of all student actions observed during $\mathcal{L}_X$, the time of the beginning and end of the observed ARLE/intervention (in seconds) - $\mathcal{T}_{\mathcal{L}xb}$ and $\mathcal{T}_{\mathcal{L}xe}$, respectively:

ARLEO initial coding algorithm $\mathcal{ICA}$

Input: Video-recordings $\mathcal{V}_{\mathcal{L}x}$ for the lesson $\mathcal{L}_X$, as recorded with cameras $C_{\mathcal{L}}$, $C_{\mathcal{R}}$, where $\mathcal{V}_{\mathcal{L}xCl}$, $\mathcal{V}_{\mathcal{L}xCr} \in \mathcal{V}_{\mathcal{L}x}$, a set of students $S_{\mathcal{L}x}$ of $C_{\mathcal{L}x}$ present during the observed lesson $\mathcal{L}_X$, class $C_{\mathcal{L}x}$, date of the lesson $\mathcal{DT}_{\mathcal{L}x}$, beginning and end time of the lesson $\mathcal{L}_X$ - $\mathcal{T}_{\mathcal{L}x} = \{\mathcal{T}_{\mathcal{L}xb}, \ldots, \mathcal{T}_{\mathcal{L}xe}\}$

Output: set of all observed student actions $\mathcal{A}_{\mathcal{L}x}$ for Lesson $\mathcal{L}_X$

set $\mathcal{A}_{\mathcal{L}x} = \{\}$

for each student under observation S_O, $S_O \in S_{\mathcal{L}x}$

for each $\mathcal{T}_O \in \{\mathcal{T}_{\mathcal{L}xb}, \ldots, \mathcal{T}_{\mathcal{L}xe}\}$

/ check first the left camera recording */*

if (end of an action $\mathcal{A}_O$ is observed in $\mathcal{V}_{\mathcal{L}xClTo}$) $\wedge$ ($\mathcal{A}_O \notin \mathcal{A}_{\mathcal{L}x}$)

$\mathcal{L}_{\mathcal{A}o} = \mathcal{L}_X$, $C_{\mathcal{A}o} = C_{\mathcal{L}x}$, $\mathcal{DT}_{\mathcal{A}o} = \mathcal{DT}_{\mathcal{L}x}$, $S_{\mathcal{A}o} = S_O$,

$\mathcal{DES}_{\mathcal{A}o}$ = observer-coder provided description,

$\mathcal{T}_{\mathcal{A}ob}$ = check back in $\mathcal{V}_{\mathcal{L}x}$ and determine beginning of action (first in $\mathcal{V}_{\mathcal{L}xClTo}$ and if not found in $\mathcal{V}_{\mathcal{L}xCrTo}$)

$\mathcal{T}_{\mathcal{A}oe} = \mathcal{T}_O$

$\mathcal{A}_O = \{ \mathcal{L}_{\mathcal{A}o}, C_{\mathcal{A}o}, \mathcal{DT}_{\mathcal{A}o}, S_O, \mathcal{DES}_{\mathcal{A}so}, \mathcal{T}_{\mathcal{A}ob}, \mathcal{T}_{\mathcal{A}oe} \}$

$\mathcal{A}_{\mathcal{L}x} = \mathcal{A}_{\mathcal{L}x} \cup \{\mathcal{A}_O\}$

/ check second the right camera recording */*

if (end of an action $\mathcal{A}_O$ is observed in $\mathcal{V}_{\mathcal{L}xCrTo}$) $\wedge$ ($\mathcal{A}_O \notin \mathcal{A}_{\mathcal{L}x}$)

$\mathcal{L}_{\mathcal{A}o} = \mathcal{L}_X$, $C_{\mathcal{A}o} = C_{\mathcal{L}x}$, $\mathcal{DT}_{\mathcal{A}o} = \mathcal{DT}_{\mathcal{L}x}$, $S_{\mathcal{A}o} = S_O$,

$\mathcal{DES}_{\mathcal{A}o}$ = observer-coder provided description,

$\mathcal{T}_{\mathcal{A}ob}$ = check back in $\mathcal{V}_{\mathcal{L}x}$ and determine beginning of action (first in $\mathcal{V}_{\mathcal{L}xCrTo}$ and if not found in $\mathcal{V}_{\mathcal{L}xClTo}$)

$\mathcal{T}_{\mathcal{A}oe} = \mathcal{T}_O$

$\mathcal{A}_O = \{ \mathcal{L}_{\mathcal{A}o}, C_{\mathcal{A}o}, \mathcal{DT}_{\mathcal{A}o}, S_O, \mathcal{DES}_{\mathcal{A}so}, \mathcal{T}_{\mathcal{A}ob}, \mathcal{T}_{\mathcal{A}oe} \}$

$\mathcal{A}_{\mathcal{L}x} = \mathcal{A}_{\mathcal{L}x} \cup \{\mathcal{A}_O\}$

Algorithm 5.1 ARLEO initial coding algorithm $\mathcal{ICA}$

3. *Focused coding* – analysis of initial codes $\mathcal{A}_{\mathcal{L}x}$ for a lesson $\mathcal{L}_X$ yields focused codes $\mathcal{F}_{\mathcal{L}x}$, where $\mathcal{F}_i = \{A_{\mathcal{F}i}, \mathcal{DES}_{\mathcal{F}i}, \mathcal{E}_{\mathcal{F}i}\}$, $\mathcal{F}_i \in \mathcal{F}_{\mathcal{L}x}$, with $\mathcal{A}_{\mathcal{F}i}$ representing a set of initial codes that are associated with $\mathcal{F}_i$, $\mathcal{DES}_{\mathcal{F}i}$ description of the focused code $\mathcal{F}_i$, and $\mathcal{E}_{\mathcal{F}i}$ represents all engagement categories that the focused code $\mathcal{F}_i$ is associated with (the categories of engagement are behavioural ($\mathcal{E}_{\mathcal{B}}$), emotional ($\mathcal{E}_{\mathcal{E}}$), cognitive ($\mathcal{E}_C$), non-engagement ($\mathcal{E}_{\mathcal{N}}$) and aggregated engagement ($\mathcal{E}_{\mathcal{A}}$), the associations being done in the next step, *axial coding*). Focused codes $\mathcal{F}_{\mathcal{L}x}$ are more directed, selective and conceptual than initial codes, allowing for identification of initial codes that can be merged, but in a way that captures the initial data completely for the intended purpose [139]. This means creation of focused codes considering that they should represent comparable engagement situations; each initial code is associated with a focused code (i.e., the observed initial code $\mathcal{A}_O$ is associated to the set $\mathcal{A}_{\mathcal{F}i}$ of related initial codes for an observed/determined focused code $\mathcal{F}_i$). Comparable engagement situations means that all engagement-relevant characteristics of the description of the observed initial code $\mathcal{DES}_{\mathcal{A}o}$ are present in the description of the focused code $\mathcal{DES}_{\mathcal{F}i}$. In [132], an example given is that „*initial codes of "Asking for teacher assistance", "Discussing with researcher", "Discussing with teacher", "Finished / go-again discussion", "Going to teacher for help", "Going to researcher to claim completion" have all been coded as the focused code "Interaction with authority figure", as they all represent [students] trying to understand the task or the next steps thereof through emotional engagement of engaging with an authority figure in the classroom.*" This is taking into account that „*if an element is missing or is not exactly that in an initial code, a separate focused code should be considered. In the example, the initial code of "teacher intervening when*

student is scanning all markers" has the element of student-authority figure interaction, but is missing the on-task element, thus it being more appropriate to associate it with a different focused code ("Cheating requiring intervention" in the example)." [132] Descriptions of focused codes should be generalisations of the initial codes where the generalised description captures all the relevant elements of the initial code. This is represented algorithmically with the following Algorithm 5.2.; the creation of said associations with engagement categories is explored in the next section, *axial coding*, and in Algorithm 5.3.

ARLEO focused coding algorithm $\mathcal{FCA}$

Input: initial codes $\mathcal{A}_{\mathcal{L}x}$ for a lesson $\mathcal{L}_X$

Output: focused codes $\mathcal{F}_{\mathcal{L}x}$ for lesson $\mathcal{L}_X$

set $\mathcal{F}_{\mathcal{L}x} = \{\}$

for each $\mathcal{A}_O$, $\mathcal{A}_O \in \mathcal{A}_{\mathcal{L}x}$

if $\exists\ \mathcal{F}_O \in \mathcal{F}_{\mathcal{L}x}$ where $\mathcal{DES}_{\mathcal{A}o}$ is comparable to $\mathcal{DES}_{\mathcal{F}o}$

$\mathcal{A}_{\mathcal{F}o} = \mathcal{A}_{\mathcal{F}o} \cup \{\mathcal{A}_O\}$

else

$\mathcal{F}_O = \{\mathcal{A}_{\mathcal{F}o} = \{\mathcal{A}_O\}, \mathcal{DES}_{\mathcal{F}o} = \text{generalized } \mathcal{DES}_{\mathcal{A}o}, \mathcal{E}_{\mathcal{F}o} = \{\}\}$

$\mathcal{F}_{\mathcal{L}x} = \mathcal{F}_{\mathcal{L}x} \cup \{\mathcal{F}_O\}$

Algorithm 5.2 ARLEO focused coding algorithm $\mathcal{FCA}$

4. *Axial coding* – tying together of fragmented data created by initial coding into coherent units by relating subcategories to categories [139]. In the ARLEO context, this is done by associating each observed/determined focused code $\mathcal{F}_O$ from the set of focused codes $\mathcal{F}_{\mathcal{L}x}$ for lesson $\mathcal{L}_X$ with categories of engagement $\mathcal{E}_{\mathcal{F}o}$ (those being behavioural ($\mathcal{E}_{\mathcal{B}}$), emotional ($\mathcal{E}_{\mathcal{E}}$), cognitive ($\mathcal{E}_{\mathcal{C}}$), non-engagement ($\mathcal{E}_{\mathcal{N}}$) and aggregated engagement ($\mathcal{E}_{\mathcal{A}}$)) that the initial codes $\mathcal{A}_{\mathcal{F}o}$ that are defined by that focused code through its generalized description $\mathcal{DES}_{\mathcal{F}o}$ are considered to display. Thus, for each initial action, via focused codes and axial coding, it is possible to determine the categories of engagement that were observed during that action. The algorithm for axial coding is presented in Algorithm 5.3.

ARLEO axial coding algorithm $\mathcal{ACA}$

Input: focused codes $\mathcal{F}_{\mathcal{L}x}$ for a lesson $\mathcal{L}_X$

Output: focused codes $\mathcal{F}_{\mathcal{L}x}$ for lesson $\mathcal{L}_{X,}$ enriched with engagement category association $\mathcal{E}_{\mathcal{F}o}$

for each $\mathcal{F}_O$, $\mathcal{F}_O \in \mathcal{F}_{\mathcal{L}x}$

set $\mathcal{E}_{\mathcal{F}o} = \{\}$

if $\mathcal{DES}_{\mathcal{F}o}$ describes $\mathcal{E}_C$

$\mathcal{E}_{\mathcal{F}o} = \mathcal{E}_{\mathcal{F}o} \cup \{\mathcal{E}_C\}$

if $\mathcal{DES}_{\mathcal{F}o}$ describes $\mathcal{E}_{\mathcal{E}}$

$\mathcal{E}_{\mathcal{F}o} = \mathcal{E}_{\mathcal{F}o} \cup \{\mathcal{E}_{\mathcal{E}}\}$

if $\mathcal{DES}_{\mathcal{F}o}$ describes $\mathcal{E}_{\mathcal{B}}$

$\mathcal{E}_{\mathcal{F}o} = \mathcal{E}_{\mathcal{F}o} \cup \{\mathcal{E}_{\mathcal{B}}\}$

if $\mathcal{E}_C \in \mathcal{E}_{\mathcal{F}o} \vee \mathcal{E}_{\mathcal{E}} \in \mathcal{E}_{\mathcal{F}o} \vee \mathcal{E}_{\mathcal{B}} \in \mathcal{E}_{\mathcal{F}o}$

$\mathcal{E}_{\mathcal{F}o} = \mathcal{E}_{\mathcal{F}o} \cup \{\mathcal{E}_{\mathcal{A}}\}$

if $\mathcal{DES}_{\mathcal{F}o}$ describes $\mathcal{E}_{\mathcal{N}}$

$\mathcal{E}_{\mathcal{F}o} = \mathcal{E}_{\mathcal{F}o} \cup \{\mathcal{E}_{\mathcal{N}}\}$

Algorithm 5.3 ARLEO axial coding algorithm $\mathcal{ACA}$

5. *Period coding* – discretization of the lesson into engagement periods – the entire duration $\mathcal{D}_{\mathcal{L}x}$ of the lesson $\mathcal{L}_X$ is divided into periods $\mathcal{P}_{\mathcal{L}x}$ (with, by default, a 15-seconds period duration $\mathcal{D}_{\mathcal{P}}$), starting from the time used as the 0-offset during initial coding. For each student under observation S_O, their engagement during the periods for the 5 categories of engagement are determined to be either true or false. This is based on comparing the beginning and end time of the period ($\mathcal{T}_{\mathcal{P}i} = \{\mathcal{T}_{\mathcal{P}ib}, \mathcal{T}_{\mathcal{P}ie}\}$, for $\mathcal{P}_i \in \mathcal{P}_{\mathcal{L}x}$, i = $\{1, \ldots, \mathcal{D}_{\mathcal{L}x} / \mathcal{D}_{\mathcal{P}}\}$) against all observed actions $\mathcal{A}_{So}$ coded for the student under observation S_O, where the student under observation S_O is considered to be engaged during the period under observation $\mathcal{P}_O$ ($\mathcal{P}_O = \{\mathcal{T}_{\mathcal{P}o}, S_O, \mathcal{E}_{\mathcal{P}o}\}$, with $\mathcal{T}_{\mathcal{P}o}$ being the beginning and end time of the period, S_O being the observed student the period is associated with, and $\mathcal{E}_{\mathcal{P}o}$ being the categories of engagement observed in that period,

$\mathcal{P}_O \in \mathcal{P}_{So}$, $\mathcal{P}_{So}$ representing the set of periods for the student S_O, with $\mathcal{P}_{Soi} \in \mathcal{P}_{So} \in \mathcal{P}_{\mathcal{L}x}$, i = {1, …, $\mathcal{D}_{\mathcal{L}x} / \mathcal{D}_{\mathcal{P}}$}) in a certain category of engagement (and thus associated with $\mathcal{E}_{\mathcal{P}o}$) if at least one instance of such engagement has been coded for the student's actions, which is determined by comparing the category association of the focused codes to which the initial codes of the student's actions belong as well as comparing the initial codes beginnings and ends to the period beginning and end. If the initial code time falls into the period being analysed or partially overlaps it, the student is engaged in the categories of engagement to which the associated focused code belongs to. Period coding can be algorithmically represented via Algorithm 5.4.

ARLEO period coding algorithm $\mathcal{PCA}$

Input: lesson $\mathcal{L}_X$, initial codes $\mathcal{A}_{\mathcal{L}x}$, focused codes $\mathcal{F}_{\mathcal{L}x}$ for lesson $\mathcal{L}_X$,

period duration $\mathcal{D}_{\mathcal{P}}$

Output: periods $\mathcal{P}_{\mathcal{L}x}$ for lesson $\mathcal{L}_X$

set $\mathcal{P}_{\mathcal{L}x} = \{\}$

for each S_O, $S_O \in S_{\mathcal{L}x}$

$\mathcal{P}_{So} = \{\mathcal{P}_{So1}, \ldots, \mathcal{P}_{Soi}, \ldots, \mathcal{P}_{Son}\}$ where $\mathcal{T}_{\mathcal{P}soib} = (i - 1) \cdot \mathcal{D}_{\mathcal{P}}$, $\mathcal{T}_{\mathcal{P}soie} = i \cdot \mathcal{D}_{\mathcal{P}}$,

$i = \{1, \ldots, n = \mathcal{D}_{\mathcal{L}x} / \mathcal{D}_{\mathcal{P}}\}$,

$\mathcal{P}_{Soi} = \{\mathcal{T}_{\mathcal{P}soi} = \{\mathcal{T}_{\mathcal{P}soib}, \mathcal{T}_{\mathcal{P}soie}\}, S_{\mathcal{P}soi} = S_O, \mathcal{E}_{\mathcal{P}soi} = \{\}\}$

for each $\mathcal{P}_{SoO}$, $\mathcal{P}_{SoO} \in \mathcal{P}_{So}$

if $\exists\ \mathcal{F}_O \in \mathcal{F}_{\mathcal{L}x}$ where $(\mathcal{E}_C \in \mathcal{E}_{\mathcal{F}o}) \wedge$

$(\exists \mathcal{A}_O \in \mathcal{A}_{\mathcal{F}o}$ where $S_{\mathcal{A}o} = S_O \wedge$

$\neg(\mathcal{T}_{\mathcal{A}ob} > \mathcal{T}_{\mathcal{P}SoOe} \vee \mathcal{T}_{\mathcal{A}oe} \leq \mathcal{T}_{\mathcal{P}SoOb}))$

$\mathcal{E}_{\mathcal{P}SoO} = \mathcal{E}_{\mathcal{P}SoO} \cup \{\mathcal{E}_C\}$

if $\exists\ \mathcal{F}_O \in \mathcal{F}_{\mathcal{L}x}$ where $(\mathcal{E}_{\mathcal{E}} \in \mathcal{E}_{\mathcal{F}o}) \wedge$

$(\exists \mathcal{A}_O \in \mathcal{A}_{\mathcal{F}o}$ where $S_{\mathcal{A}o} = S_O \wedge$

$\neg(\mathcal{T}_{\mathcal{A}ob} > \mathcal{T}_{\mathcal{P}SoOe} \vee \mathcal{T}_{\mathcal{A}oe} \leq \mathcal{T}_{\mathcal{P}SoOb}))$

$\mathcal{E}_{\mathcal{P}SoO} = \mathcal{E}_{\mathcal{P}SoO} \cup \{\mathcal{E}_{\mathcal{E}}\}$

if $\exists\ \mathcal{F}_O \in \mathcal{F}_{\mathcal{L}x}$ where $(\mathcal{E}_{\mathcal{B}} \in \mathcal{E}_{\mathcal{F}o}) \wedge$

$(\exists \mathcal{A}_O \in \mathcal{A}_{\mathcal{F}o}$ where $S_{\mathcal{A}o} = S_O \wedge$

$\neg(\mathcal{T}_{\mathcal{A}ob} > \mathcal{T}_{\mathcal{P}SoOe} \vee \mathcal{T}_{\mathcal{A}oe} \leq \mathcal{T}_{\mathcal{P}SoOb}))$

$\mathcal{E}_{\mathcal{P}SoO} = \mathcal{E}_{\mathcal{P}SoO} \cup \{\mathcal{E}_{\mathcal{B}}\}$

if $\exists\ \mathcal{F}_O \in \mathcal{F}_{\mathcal{L}x}$ where $(\mathcal{E}_{\mathcal{A}} \in \mathcal{E}_{\mathcal{F}o}) \wedge$

$(\exists \mathcal{A}_O \in \mathcal{A}_{\mathcal{F}o}$ where $S_{\mathcal{A}o} = S_O \wedge$

$\neg(\mathcal{T}_{\mathcal{A}ob} > \mathcal{T}_{\mathcal{P}SoOe} \vee \mathcal{T}_{\mathcal{A}oe} \leq \mathcal{T}_{\mathcal{P}SoOb}))$

$\mathcal{E}_{\mathcal{P}SoO} = \mathcal{E}_{\mathcal{P}SoO} \cup \{\mathcal{E}_{\mathcal{A}}\}$

if $\exists\ \mathcal{F}_O \in \mathcal{F}_{\mathcal{L}x}$ where $(\mathcal{E}_{\mathcal{N}} \in \mathcal{E}_{\mathcal{F}o}) \wedge$

$(\exists \mathcal{A}_O \in \mathcal{A}_{\mathcal{F}o}$ where $S_{\mathcal{A}o} = S_O \wedge$

$\neg(\mathcal{T}_{\mathcal{A}ob} > \mathcal{T}_{\mathcal{P}SoOe} \vee \mathcal{T}_{\mathcal{A}oe} \leq \mathcal{T}_{\mathcal{P}SoOb}))$

$\mathcal{E}_{\mathcal{P}SoO} = \mathcal{E}_{\mathcal{P}SoO} \cup \{\mathcal{E}_{\mathcal{N}}\}$

$\mathcal{P}_{\mathcal{L}x} = \mathcal{P}_{\mathcal{L}x} \cup \mathcal{P}_{SoO}$

Algorithm 5.4 ARLEO period coding algorithm $\mathcal{PCA}$

The overall ARLEO process flow is thusly described with Algorithm 5.5.

ARLEO process flow algorithm

Input: lesson $\mathcal{L}_X$, period duration $\mathcal{D}_{\mathcal{P}}$

Output: periods $\mathcal{P}_X$ for lesson $\mathcal{L}_X$

Video-record the lesson $\mathcal{L}_X$ thus generating video $\mathcal{V}_{\mathcal{L}xCl}$ and $\mathcal{V}_{\mathcal{L}xCr}$, $\mathcal{V}_{\mathcal{L}xCl}$, $\mathcal{V}_{\mathcal{L}xCr} \in \mathcal{V}_{\mathcal{L}x}$

$S_{\mathcal{L}x}$ = students present during $\mathcal{L}_X$

$C_{\mathcal{L}x}$ = class being observed during $\mathcal{L}_X$

$\mathcal{DT}_{\mathcal{L}x}$ = date of $\mathcal{L}_X$

$\mathcal{T}_{\mathcal{L}xb}$ = normalized beginning of lesson $\mathcal{L}_X$

$\mathcal{T}_{\mathcal{L}xe}$ = normalized end of lesson $\mathcal{L}_X$

$\mathcal{T}_{\mathcal{L}x} = \{\mathcal{T}_{\mathcal{L}xb}, \mathcal{T}_{\mathcal{L}xe}\}$

$\mathcal{A}_{\mathcal{L}x} = \mathcal{ICA}\ (\mathcal{V}_{\mathcal{L}xCl}, \mathcal{V}_{\mathcal{L}xCr}, S_{\mathcal{L}x}\ \mathcal{L}_X, C_{\mathcal{L}x}, \mathcal{DT}_{\mathcal{L}x}, \mathcal{T}_{\mathcal{L}x})$

$\mathcal{F}_{\mathcal{L}x} = \mathcal{ACA}\ (\mathcal{FCA}\ (\mathcal{A}_{\mathcal{L}x}))$

$\mathcal{P}_{\mathcal{L}x} = \mathcal{PCA}\ (\mathcal{L}_X, \mathcal{A}_{\mathcal{L}x}, \mathcal{F}_{\mathcal{L}x}, \mathcal{D}_{\mathcal{P}})$

Algorithm 5.5 ARLEO process flow algorithm

Appendices A and B present the necessary Excel templates and periodic coding algorithm code for an implementation of the ARLEO algorithm, respectively.

Once the period coding has been completed, it is possible to apply both parametric and non-parametric tests to the results, in line with learning analytics approaches. In particular, as explored in detail in the next section and in chapter 7, it is possible to use both statistical tests as well as timeline analysis to determine, on the basis of the number of students experiencing a category of engagement in each period, the level of engagement (per the different categories), as well as when certain phenomena, such as peaks of engagement, rise in engagement, drop of in engagement, crossing of engagement and non-engagement trends etc. occur. This allows for qualitative comparative analysis between statistical information and timeline phenomena between different observed lessons (and their experimental set-ups).

5.3. Consistency of the ARLEO observational instrument

ARLEO, like other observational instruments, is inherently subjective due to the involvement of observer-coders who need to make determinations on how to code certain student actions, assign focus codes and engagement categories. Thus, it must be subjected to inter-rater reliability and reliability coefficient (for internal consistency) checks to ensure basic soundness.

The nature of continuous recording and the dynamic development of the catalogue provides an impediment to such a check, as each rater is unlikely to code initial codes with beginning and ending times aligned to the second, nor develop the same focus codes. However, since the engagement categorisation is fixed, as is the period grid (if agreed to use the same period length, the default being 15 seconds), following period coding it is possible to compare engagement categories at period level for each student between different raters.

Therefore, an inter-rater reliability check was performed based on a dataset containing 3000 period data points derived from ARLEO coding by two different observer-coders, with each data point representing the engagement categorisation of a single student over a single period during a specific lesson held at a specific date. This inter-rater reliability check was performed after an initial pass (i.e., without any coordination or alignment in rating by the raters), yielding an 86% match with a Cohen's κ of $\kappa=.700$, $p<.0005$, indicating good inter-rater reliability. In practice, with mutual collaboration in defining focused codes and their engagement categorisation by raters, it would be possible to increase this figure even further and such an approach is thus recommended for users of ARLEO if they need to use multiple raters to rate different lessons, students or otherwise decide to split up the rating work.

In addition, a reliability coefficient check should be made to address internal consistency, as any observational instrument should, if sound, in its results, conform to the assumptions about independent unidimensional variable contributions to results embedded in its model and the correlations between them. This can be tested with the statistical tool of Cronbach's α [141]. When applied to results of the use of ARLEO (the dataset in question being explored in detail in chapter 7), exploring the different independently coded engagement categories (including an inverse of non-engagement as necessary for application of Cronbach's α) during ARLE use in the classroom, as segmentized into period data points via the periodic coding, the result of .824 for Cronbach's α is achieved, which is above the thresholds of .7 and .8 commonly associated with early and applied research, respectively [142].

The model for ARLEO assumes independently coded categories of engagement – cognitive, behavioural, and emotional, as well as non-engagement. In addition, there is the dependent variable of aggregate engagement, which is based on the presence of either cognitive, behavioural, or emotional engagement. The model therefore assumes that there will be correlation between the three independent categories of positive engagement and aggregate engagement as well as inverse correlation between aggregate and non-engagement (i.e. in the ideal case, students should be either positively or negatively engaged, but not coded for both at the same time). Those assumptions are met on a statistical level, with aggregate engagement correlating very significantly with cognitive engagement (at .971) and to a more limited, but still significant, extent with behavioural and emotional engagement (.417 and .261), respectively. There is also a very significant inverse correlation of .852 between aggregate and non-engagement.

Further examining the results via Cronbach's α if-item-deleted analysis shows the potential, as expected, of increasing the reliability coefficient with removal of behavioural (to .858) or emotional (to .874) engagement. Removal of other categories would lead to significantly lower internal consistency – to .683 with removal of cognitive engagement, to .674 with the removal of aggregate engagement and to .730 with the removal of non-engagement. Those results show that the ARLEO observational instrument is highly consistent with regards to examining cognitive engagement and non-engagement and is borderline consistent (taking the threshold of .7, which is considered to be a non-hard threshold [142]) if used to examine only behavioural and emotional engagement (without cognitive), allowing it to be overall considered a consistent observational instrument.

6. MODEL OF A SYSTEM FOR SUPPORTING LEARNING WITH AUGMENTED REALITY BASED ON ENGAGEMENT AND LEARNING ANALYTICS

In this chapter a model of an educational support system is presented for developing and deploying ARLEs in the early primary school setting. The model is based on the techno-pedagogical affordance considerations developed through STAR-ARLE (chapter 3) and the review of ARLEs in the field through the STAR-ARLE rubric (coloured yellow in Fig. 6.1). Following its development in the first part of this chapter, the model (coloured green in Fig. 6.1) is instantiated as part of the SCOLLAm platform (as described in the latter sections of this chapter) and applied in experiments to determine the engagement benefits of ARLEs in early primary school, as explored in the next chapter (shaded in Fig. 6.1).

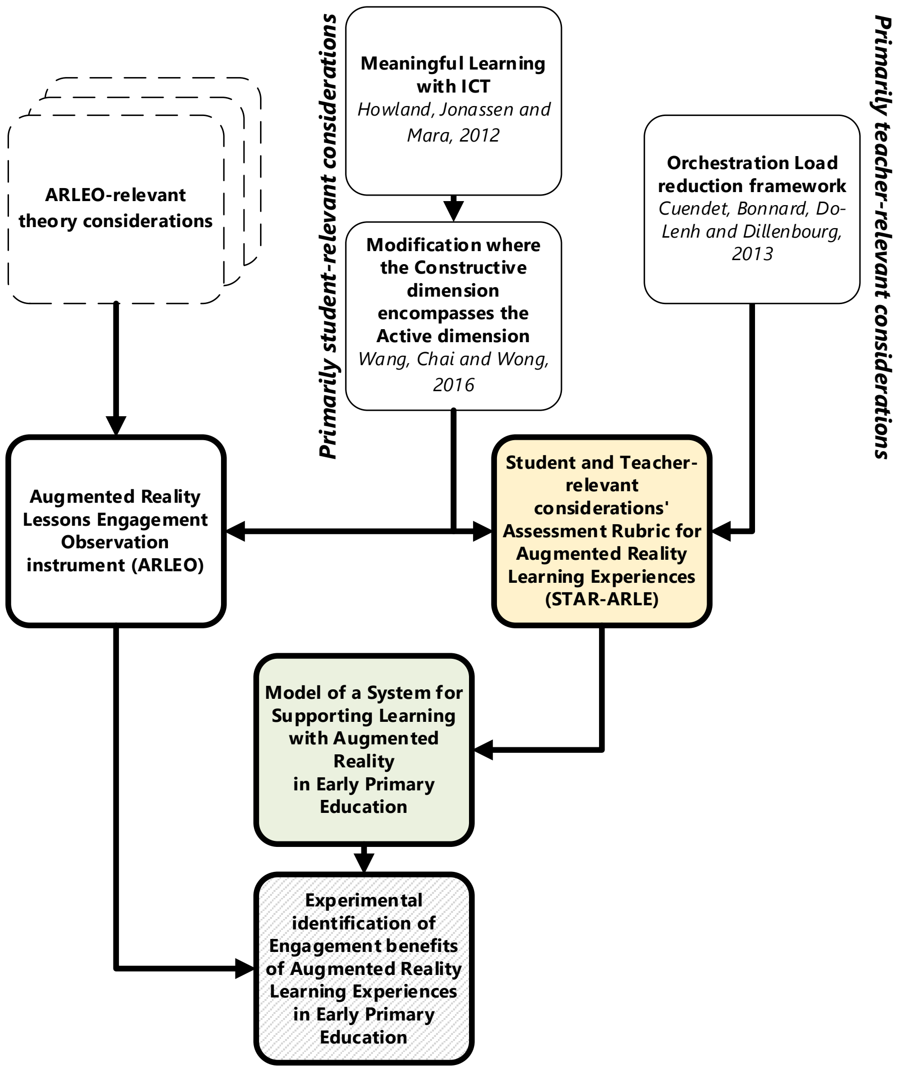

Fig. 6.1. Overview of the context of the model within the theory and contributions relevant to this thesis, with highlights for chapter 6. Expanded from Fig. 1 in [21].

6.1. Model requirements and design considerations

When observing ARLE maturity through the lens of the STAR-ARLE rubric, certain key affordance requirements shape the basic decisions regarding the design:

- It is clear from the review of the field presented in chapter 3 that student-related considerations can be mostly addressed with standalone ARLE clients and are mainly a question of the affordances that the ARLE client itself is offering. Certain workarounds may be required if the ARLE is stand-alone (such as basing cooperation not as a technological affordance but on real-world cooperation through lesson design). This is not the case for teacher-focused affordances which require an integrated infrastructure approach to enable them, with the noted exception of user experience minimalism considerations, which are ARLE client focused.
- To fully fulfil teacher-oriented affordances (orchestration load reduction affordances), it is necessary to build capability into the model of transfer of data between the system and other systems or between lesson (or lesson components) in the system (integration affordance), affordances for teacher empowerment during the execution of the ARLE (capability to intervene), affordances for teacher awareness so that the teacher can see in real-time student progress or at least after the conclusion of the ARLE the results and capability for the teacher to adjust the ARLE to facilitate necessary changes, potentially both during the preparation of the ARLE and during execution (flexibility affordance).
- With regards to preparation flexibility, research on a number of ARLE systems have shown that having teacher lesson design capabilities [55], [123], [143], [144] is a good way to enable teachers to be able to adjust the lesson and the ARLE in preparation of its execution, not requiring designer / coder assistance to change the ARLE; therefore, ideally, AR capabilities should be implemented in fairly generic ways, while the content to populate them should be susceptible to teacher-level design via some kind of design tool.
- As the review of ARLEs [21] has shown poor maturity in the field with regards to teacher-oriented orchestration load reduction affordances, any new model for systems for ARLEs should take this into account and include those affordance considerations as key requirements.

Based on those key affordance requirements, the following system technical design requirements become clear:

- The system model should be based on a distributed architecture, with database and core server components separated from client-viewer components, to allow for the necessary teacher-oriented orchestration load reduction affordances.
- The system should be set up in such a way that there is a common content database which is then accessible in appropriate ways through different user interfaces, which are accessing the server component through industry standard communication interfaces, which address the different affordance requirements.
- Techers should have access to their own interfaces to give them affordances for integration, empowerment, awareness, and flexibility, including potential for lesson design facilities, tools for real-time statistical follow-up of student performance and/or classroom-level displays tracking student performance.
- There should be capability for seamless transition from any non-ARLE materials to the ARLE experience and back, to allow for an integrated experience and an easy way to enrich the ARLE experience with supporting (bookending) content that is easier to develop than complex AR content.
- All user interfaces should be developed with the consideration of minimalism in mind, to facilitate orchestration load reduction.

Based on those considerations, the Model of a system for supporting learning with augmented reality based on engagement and learning analytics is proposed in the diagram in Fig. 6.2 and is explored in more detail in the following pages. In the model, server components are indicated in blue, and client components are indicated in yellow.

Exploring the model, we can observe that the system is envisioned as a server component to which various clients (both interactive and view-only) connect to for content delivery and information exchange. As depicted later on in Fig. 6.3., the various components can be classified as certain types of tooling which provide the necessary affordances (explored in chapter 3), with student-related (Meaningful learning with ICT-derived) affordances being indicated in green and teacher-related (Orchestration load reduction framework-derived) affordances being indicated in purple.

As the base of the system, the *system backend* can be identified, which is comprised of the *system core* and the *content database.* Built on top of that base, the components which are operated by the teacher can be identified in the *teacher tools*. Those tools are necessary to develop the ARLEs to be deployed (through *lesson designer and parametrization tool(s)*) as well as to assist the teacher in managing the ARLE during execution (*teacher live interface*).

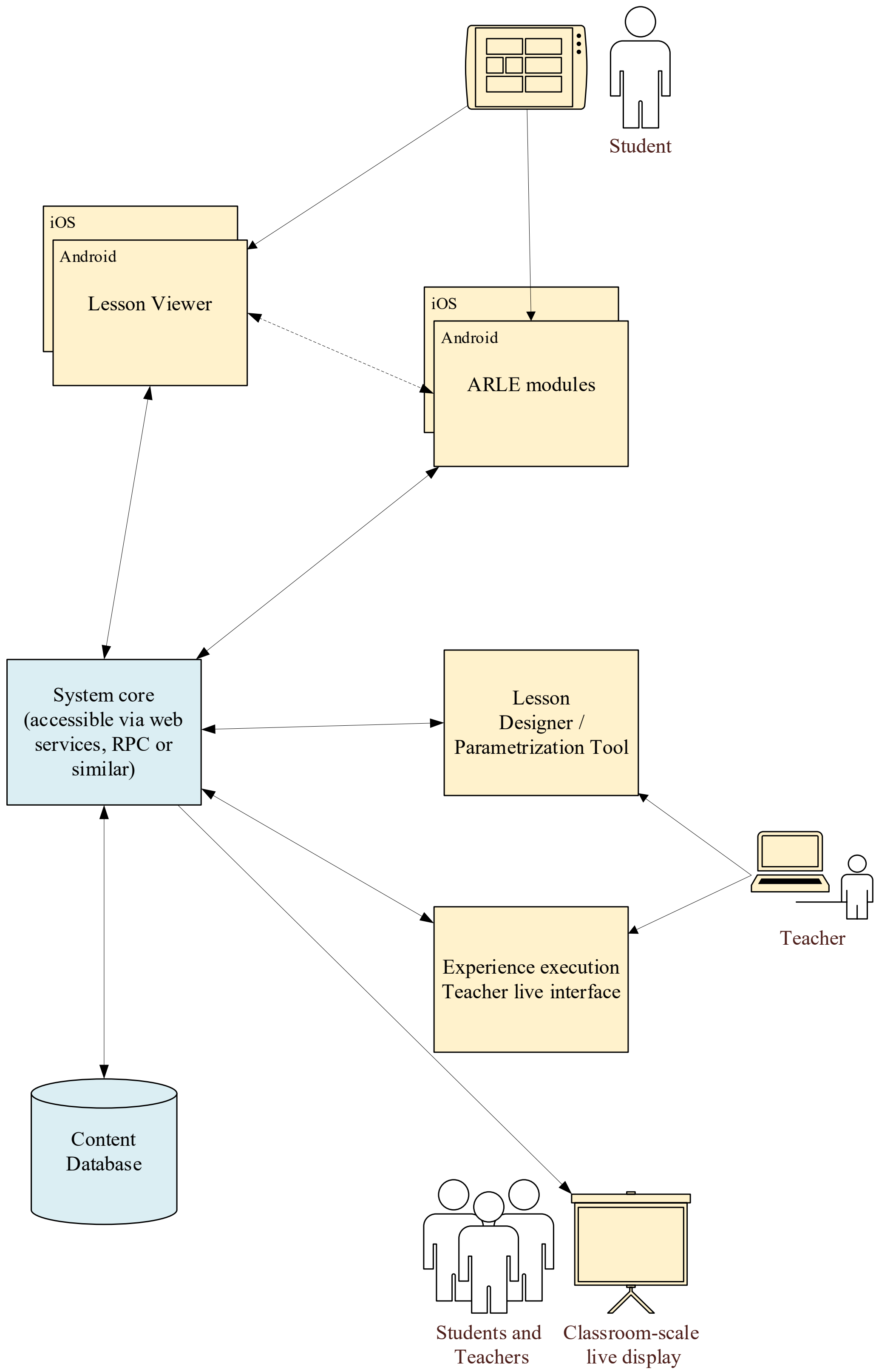

Fig. 6.2. High-level architecture diagram of the model of a system for supporting learning with augmented reality based on engagement and learning analytics.

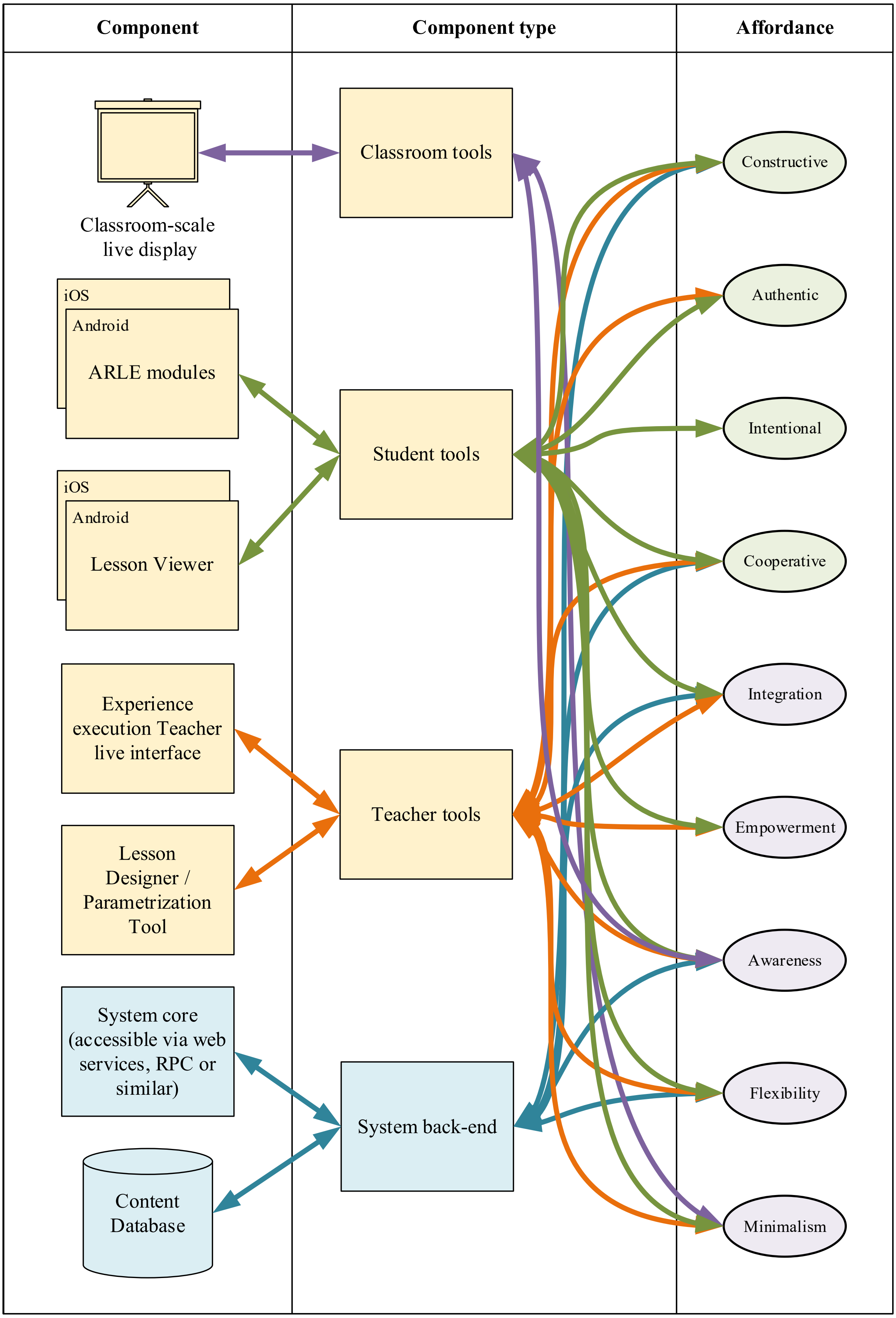

Fig. 6.3. Diagram of model component categorisation and the relationship (applicability) of STAR-ARLE affordances to each category of the components of the presented model

Once an ARLE has been developed, it is experienced by the students through *student tools* - the *lesson viewer* and *ARLE modules.* A classroom level view can be considered through *classroom tools* represented by the component *classroom-scale live display.* In the following sections, the associated affordances analysis for each type and component is provided.

6.1.1. System back-end

The *system back-end* comprises the *system core* and the *content database*. As the base for the entire system, *system back-end* components must enable all the technological affordances needed in the user-oriented components. However, it is not exposed directly to the users, so the affordances that are more reliant on the user experience are not of concern with this component. Therefore, the affordances of *constructive, cooperative, integration, awareness* and *flexibility* must be considered.

In particular, the *system core* represents the core server component. It should facilitate any information exchange necessary between the different components, as well as integration between the components and other systems, as well as reporting. It should be developed with appropriate interfaces in mind to allow connection of the various clients, such as through web services, RPC, or similar industry standard approaches. It should facilitate the other components being able to read and write to the content databases, to keep logs of activity, and other necessary data exchange. It should support affordances as described in Table 6.1.

TABLE 6.1
SUPPORT APPROACH FOR RELEVANT AFFORDANCES OF THE SYSTEM CORE

Dimension	Support approach
Cooperative	If there is a desire to support cooperative affordances on a technological level, enough facilities must be exposed to allow cooperative work between the clients running on student smartphones and/or tablets via appropriate protocols (real-time or through exchange of data via web-services).
Integration	The system core should allow for integration of activities across activities hosted in the system, whether ARLE based or otherwise, as well as, if relevant for the context of the deployment of the system, with other Learning Management Systems (LMS), to make it as easy as possible to make an integrated approach to learning topics.
Awareness	The system core should allow the gathering of statistics on the use of ARLEs to be able to provide reporting after the lesson (or even during the lesson – see the live display component and teacher live interfaces) on student activity and results during the lesson to teachers and, potentially, ARLE designers.

A well-developed *content database* represents the critical component of the system. It should be able to contain the static contents of the experience as well as defining the interactive components (such as questionnaires and similar) to support constructive student learning. It is important that the content should be defined as much as possible in a pedagogically structured rather than technologically structured fashion, to enable easier reuse and format-shifting, increasing flexibility of the system. The related affordance analysis is presented in Table 6.2.

TABLE 6.2
SUPPORT APPROACH FOR RELEVANT AFFORDANCES OF THE CONTENT DATABASE

Dimension	Support approach
Constructive	ARLEs should support constructive knowledge acquisition by students. While building facilities for synthesis and reflection is more of a question of lesson design rather than system model, affordances should be considered to support such knowledge construction. As noted by Sheehy et al. [39], this is often tied to the cooperative dimension by enabling facilities for student information exchange, both peer to peer and student – teacher. Those should be envisioned in the database design by enabling appropriate references to learning materials student artefacts are related to. The mid-level of constructive approaches should also be considered to enable question and answer facilities for helping test student knowledge, for which database support for developing questions and answers related to lesson materials must be developed.
Cooperative	If there is a desire to support cooperative affordances on a technological level, the content database should, as noted, allow linking of various lesson artefacts with student-generated artefacts. As well, if there are any real-time cooperative affordances designed (such as grouping with information asymmetry) the content database must support such features allowing for linking of relevant learning materials to materials for such features.
Integration	The content database should have contents stored in such a way to allow reuse and integration of various lessons and materials.
Flexibility	Data should be structured according to pedagogical lesson contents, rather than in technologically-derived ways so that it can be more easily adjusted and reused in other ARLEs or digital lessons. The AR modules for ARLE display should be able to interpret more generalized lesson data rather than the lesson data being built in a such a way that it is dependent on the technological architecture of the ARLE module.

6.1.2. Teacher tools

Teacher tools, built on top of the *system back-end*, are tools that the teachers use to set-up (*lesson designer / parametrization tool*) or run the ARLE (*teacher live interface*). Thus, the affordances of concern are all the *orchestration load* ones, as well as some of the student-oriented ones, in such that they ultimately affect *orchestration load*. In particular, those are *constructive, authentic, cooperative, integration, empowerment, awareness, flexibility, and minimalism.* The affordances analysis for the *lesson designer / parametrization tool* is presented in Table 6.3.

TABLE 6.3
SUPPORT APPROACH FOR RELEVANT AFFORDANCES OF THE LESSON DESIGNER / PARAMETRIZATION TOOL

Dimension	Support approach
Constructive	The tool should support the level of constructive affordances offered by the ARLE module used and needed by the lesson design – that is, allowing for setting up questions and answers or setting up any default information or instructions in features supporting divergent constructive student efforts.
Authentic	The lesson designer should support creation of authentic lessons which utilize ARLE module affordances in combination with the students' environment to create authentic experiences, facilitating student learning.
Cooperative	If cooperative features are desired for a lesson and are implemented in the ARLE module, the component should support appropriate cooperative work set-up in an easy fashion, both for easing lesson preparation for teachers as well as the literature shows many instances of group set-ups needing to be adjusted on the fly [48], necessitating quick intervention.
Integration	The tool should allow for integration of the ARLE into a broader lesson or the linking of the ARLE with other activities related to the topic being taught.
Flexibility	The lesson designer or parametrization tool should allow for ARLE module reuse, with easy, teacher-understandable ways to integrate and parametrize ARLE modules and link them to different contents in the content database so that they can be reused in more than one lesson. This feature should be easy to use and reliable to facilitate quick lesson adjustments on the fly or just in time before lesson commencement if needed.
Minimalism	The user interface should be minimalistic and approachable for teachers to use without being overwhelmed with options.

The *lesson designer* or *parametrization tool* is an optional component designed to allow flexible reuse and adjustment of ARLE affordances of the system, allowing for creation of bespoke lessons utilizing ARLE affordances (in case of a lesson designer) or at least parametrization of the ARLE offered by the ARLE module (in case of a parametrization tool). While the component is optional, it is difficult to imagine an ARLE module or system that has any real level of flexibility or possibility to integrate well into the activities of a lesson without it, therefore significantly increasing teacher orchestration load if not implemented.

Experience execution teacher live interface is an optional component designed with a focus on increasing affordances in the empowerment and awareness domains. In other words, allowing teachers to be able to control experience flow and adjust it to the circumstances in the classroom (empowerment aspect) as well as being able to immediately see student progress through the experience (awareness aspect). A lack of such a component means that the teacher is more limited in control and oversight the experience during experience execution. Its affordances are explored in Table 6.4.

TABLE 6.4
SUPPORT APPROACH FOR RELEVANT AFFORDANCES OF THE EXPERIENCE EXECUTION TEACHER LIVE INTERFACE

Dimension	**Support approach**
Empowerment	A teacher live interface should enable the teacher to control aspects of the ARLE for the students in real-time during execution. This means the ability to stop and (re)start the ARLE centrally and globally (for all students). A more refined implementation would involve the ability to control various parameters of the ARLE on an individual student level during execution.
Awareness	A teacher live interface should allow the teacher to get at-a-glance overviews of student progress and activity in the ARLE, facilitating the teacher's understanding of the progress of the experience and reducing orchestration load. At a minimum there should be affordances to allow the teacher to review student activity logs after the conclusion of the ARLE.
Flexibility	The component should enable the teacher to adjust various aspects of the ARLE in real time, such as parametrization (for example, difficulty or sets of questions to be used), adjust groupings (if those exist) and otherwise be able to adapt the ARLE in real time to the constraints of the classroom.
Minimalism	The user interface of any teacher live interface is key to give the teacher a tool to be confident with and confident in to make adjustments in real-time.

6.1.3. Student tools

Student tools represent the core of the ARLE user experience – they are the tools through which the student experiences the ARLE, via *ARLE modules* and optionally a *lesson viewer* supporting the non-AR elements of the learning experience. As such, in their design, all the affordances must be considered, although there are some separate considerations for *ARLE modules* (Table 6.5 and Table 6.6) and *lesson viewer* components (Table 6.7), as explored below.

ARLE modules represent the core mandatory client of the model system. They are the method by which the AR experience is delivered to the student. An ARLE module should be developed in such a way that it is not fully fixed function, but instead can be parametrized. ARLE modules can be either standalone, in which case they must be fully-fledged client applications, or they can be modules that can be invoked from the lesson viewer, if one exists, to serve up the ARLE part of the lesson.

TABLE 6.5
SUPPORT APPROACH FOR RELEVANT STUDENT-RELATED AFFORDANCES OF THE ARLE MODULES

Dimension	Support approach
Constructive	The ARLE module should, depending on the lesson design and therefore desired level of affordances consciously chosen, allow for students to be constructive, whether via convergent facilities supporting Q&A-style approaches or via supporting divergent student expression, including reflection, synthesis and experience sharing.
Authentic	The ARLE module should allow connectivity with the surrounding environment as much as possible, to aid the affordances for authenticity. Note that this aspect is primarily determined by lesson design.
Intentional	The ARLE module should support identification of student learning gaps (for example, by providing feedback to ongoing student actions) as well as scaffolding learning for the mitigation of any identified knowledge gaps.
Cooperative	If the lesson design is such that student cooperation is desired, the ARLE module should support this in the appropriate way, whether that is via direct communication with other student's tablets, via exchange of information via the server component or even simple role assignment and consequent content adaptation if the lesson is such that the teacher is giving different roles to different students.

TABLE 6.6
SUPPORT APPROACH FOR RELEVANT TEACHER-RELATED AFFORDANCES OF THE ARLE MODULES

Dimension	Support approach
Empowerment	The ARLE module should be responsive to teacher instructions regarding lesson flow, whether that is via instructions received from the server or via use of special markers by the teacher [7].
Awareness	The ARLE module should be communicating student actions to the server to allow tracking (ideally in real-time, but at minimum post-experience) student activity and the analysis thereof.
Flexibility	The ARLE module should be flexible; functionalities should not be defined in a fixed fashion in line with lesson contents, but only in line with lesson methodological approach and/or activity set-up. An ARLE module should thus be able to be integrated into multiple lessons, proving an ARLE in different well integrated contexts and which can be tweaked and adjusted to fit the circumstances in the classroom.
Minimalism	The ARLE interface should follow minimalism user experience approaches, showing only contextually relevant information and providing a streamlined, minimalistic, easy to understand experience.

A system should consider to be able to have more than one ARLE module, to be able to serve different kinds of ARLEs based on different technologies or middleware platforms. By setting up such a flexible approach, future ARLE development can be supported in a modular fashion by providing in one place the necessary infrastructure, compliant with teacher affordance requirements, while not constraining future ARLE development within the system to upgrades of a monolithic application. Communication between the lesson viewer and the ARLE module can be implemented via platform native APIs for app interaction (such as URL scheme-based app start techniques). Considering current mobile platform market shares, ARLE modules should be developed for iOS and Android, unless specific circumstances dictate otherwise (i.e., the ARLE is being developed for use in schools that have only iOS or only Android smartphones / tablets deployed).

A *lesson viewer* is an optional component that can be implemented if the overall system is a LMS with a distributed architecture where there is a desire to have flexible ARLE modules implementations, running specific ARLE modules as needed for a specific lesson. If the ARLE modules are not standalone, a *lesson viewer* application should be the entry point for students to access lessons that contain ARLEs on their tablets, with it invoking the specific ARLE module needed for the lesson.

TABLE 6.7
SUPPORT APPROACH FOR RELEVANT AFFORDANCES OF THE LESSON VIEWER

Dimension	Support approach
Integration	Lesson viewers should enable mixed experiences where parts of the experience are AR-based and parts not, facilitating content development in both parts by allowing ARLE module developers to focus on complex AR capabilities while the remaining lesson materials are developed via more traditional digital lesion approaches, including more easier implementation of flexibility, thus enriching traditional lessons while lessening the already high complexity for ARLE module developers. With such an integrated approach, designed lessons are more likely to be easier to adjust and integrate into the overall learning approach for the topic being taught, decreasing orchestration load.
Flexibility	Lesson viewers should assist with being able to deploy parametrization more easily to ARLE modules and/or facilitate use of differing ARLE modules, easing flexibility.
Minimalism	Lesson viewers should offer a minimalistic user experience to students, with easy-to-understand navigation and lesson flow.

6.1.4. Classroom tools

Optionally, *classroom* tools can also be considered in the model. A *classroom-scale live display* is a component that allows for the tracking of ARLE progress by both teachers and students, giving a global overview of the activity of the class in the ARLE. The affordances analysis is presented in Table 6.8.

TABLE 6.8
SUPPORT APPROACH FOR RELEVANT AFFORDANCES OF THE CLASSROOM-SCALE LIVE DISPLAY

Dimension	Support approach
Awareness	The main purpose of a classroom-scale live display is to increase the awareness of both teachers and students on the progress of the experience, enhancing engagement both in ARLEs [145] and elsewhere [33].
Minimalism	Any such display should be minimalistic and to the point as to not distract the students from their own ARLE efforts, but instead to complement them.

That both parts of the audience are present suggests that, rather than a technical teacher-oriented display, any classroom-scale display should ensure that the live progress data is presented in a way that encourages the students while giving a clear status overview.

6.2. Implementing the model in practice

As the SCOLLAm project was envisioned as a multiapproach pilot project, exploring differing approaches to mobile learning, to enable an efficient and holistic approach, a common SCOLLAm platform was developed which included a core SCOLLAm system based on REST web services, a common content database as well as a client application called InForm and a lesson designer called Author.

Each lesson developed for the platform starts its life in the Author lesson designer. In SCOLLAm terms, a lesson is called a module and consists of multiple sub-modules (referred to as pages or slides), which can contain basic content elements (text, images, and shapes) produced directly in Author or a so-called widget that provides access to an outside resource containing an advanced interactive experience (Fig. 6.4).

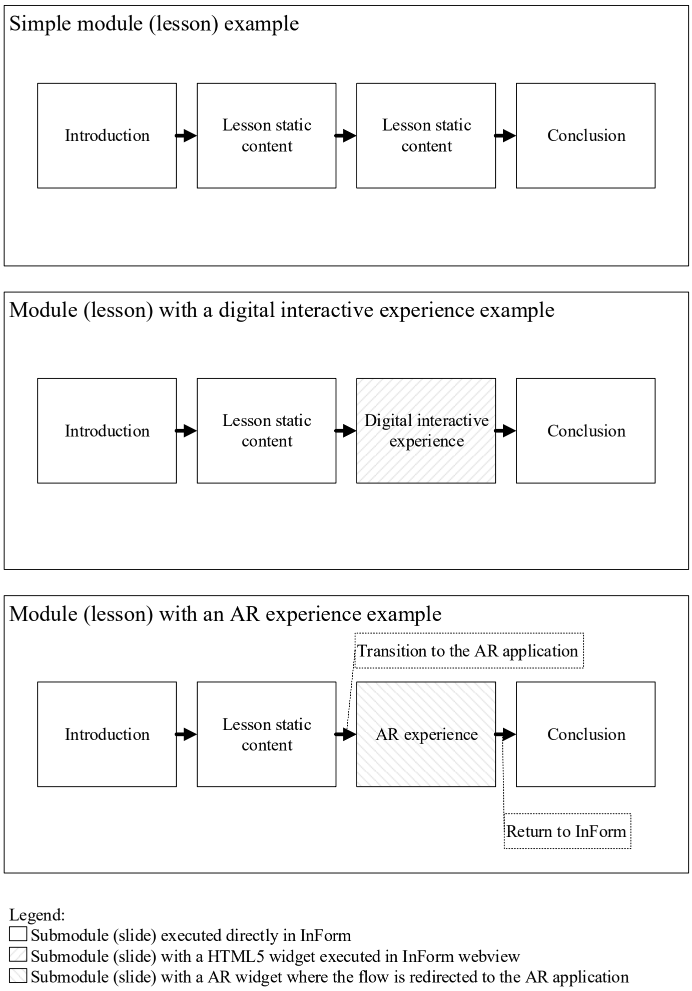

Fig. 6.4. Examples of different SCOLLAm module (lesson) designs. Originally published as Fig. 2 in [132].

Therefore, a typical lesson for SCOLLAm produced in Author consists of several introductory basic slides with refresher materials on the topic for the students and lesson instructions, followed by a widget slide with the interactive experience that is the core of the lesson and finishing with several slides that provide a conclusion of the lesson. Practical examples of such slides can be seen in Fig. 7.2, Fig. 7.3 and Fig. 7.4 in the next chapter.

All lessons are launched by students by opening them in the InForm viewer application on their tablet. InForm has been developed for Android, iOS, and Windows.

The widget facility to implement ARLEs and other advanced interactive contents allows for launching custom contents within the basic digital lesson, such as ARLEs or HTML5 content, allowing to parametrize such content and facilitating the communication between the widget content and the server (via web services). A diagram of the system infrastructure is presented in Fig. 6.5.

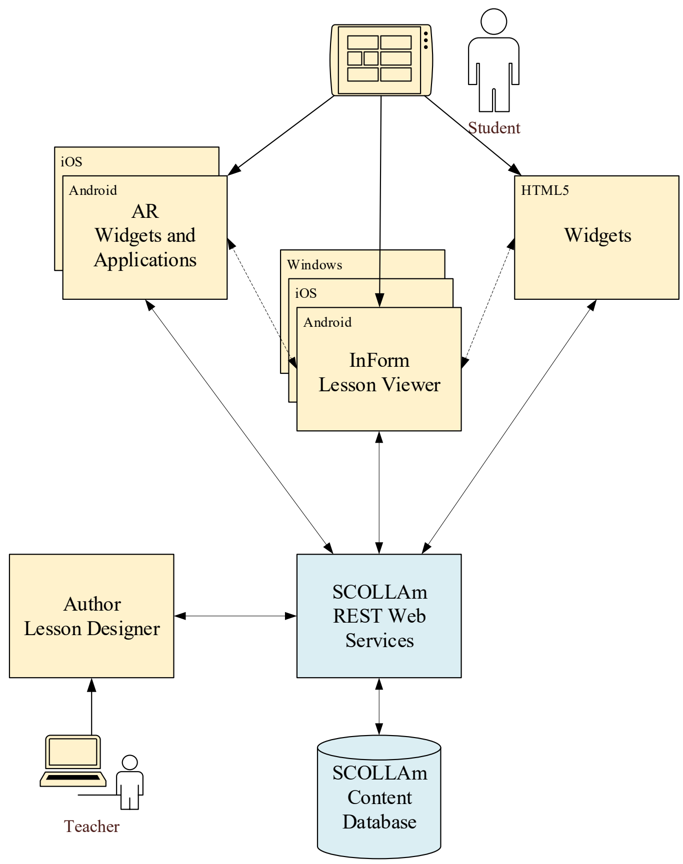

Fig. 6.5. SCOLLAm platform infrastructure diagram[2]. Adapted from Fig. 1 in [132].

[2] Note on authorship of the SCOLLAm platform: The core of the SCOLLAm platform (SCOLLAm Content Database and REST Web Services, Author and InFrom) was developed by SCOLLAm team members Ivica Botički and Tomislav Jagušt, supervising, assisting, and contributing to the development work by multiple

HTML5 widgets are initiated as a slide element of the lesson in the InForm viewer application and are instantiated through a web view iframe component, allowing for interaction of the widget with the basic content of the lesson such as navigation. They contain the logic for all the interactivity of the experience (as parametrized in the widget during lesson design in Author) and, being HTML5 based, have access to the SCOLLAm web services directly from the web view via JavaScript code.

AR widgets work in conjunction with AR modules. They are initiated as a slide element by the InForm viewer and contain metadata including parametrization (as set up in the Author module during lesson design) of the ARLE to be delivered to the AR module to set up the ARLE within the context of the lesson and previous work. Other metadata includes information on which AR module to initiate for the widget. AR modules must be installed separately from InForm on the tablets for the lesson to operate correctly. Such AR modules have been developed for Android and iOS platforms, utilizing Unity[3] and Vuforia[4] middleware. No developments were done for Windows due to the failure of Windows tablets in the market by the time of the development of the modules (2016/2017). Consequently, ARLEs for SCOLLAm were only available on Android and iOS, even though the platform otherwise supported Windows as well with InForm.

In terms of the handover between InForm and the AR modules, once the slide with the AR widget is reached, it triggers and initiates a switch of activity / app via the mechanism of URL schemas specific to the AR module it is parametrized for. As part of the switch, a platform-appropriate parametrization data package (including simple parameters as well as references to complex content) is given to the AR module which allows it to initialize itself, directly for simple parameters and by loading content from the SCOLLAm system via web services for complex content references. The AR module then takes over as the user experience for the student and continues until the ending of the ARLE, at which point inter-application communication is used to return control to the InForm viewer, along with a data package containing state and results data, allowing InForm to continue the lesson, with some final conclusionary slides if desired.

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involved Bachelor and Master-level students, as documented in their theses, with input regarding AR-necessary functionalities from the author. The author, as the research coordinator for the AR domain, supervised, assisted, and contributed to the development of AR Widgets and Applications and associated control HTML5 Widgets done by Master-level students Mirna Domančić [153], Manuela Kajkara [148], and Petra Vujević [154], as documented in their theses.

[3] Unity is a leading platform for creating and operating real-time 3D interactive content - Unity, “Unity Real-Time Development Platform | 3D, 2D VR & AR Engine”, available at: https://unity.com/ (13th March 2022)

[4] Vuforia is a leading enterprise AR platform - PTC, “Vuforia Enterprise Augmented Reality (AR) Software”, available at: https://www.ptc.com/en/products/vuforia (13th March 2022)

7. USING DIGITAL LESSONS FOR TABLET COMPUTERS WITH AUGMENTED REALITY IN EARLY PRIMARY EDUCATION

7.1. Problem statement

As indicated in section 3.6, previous examinations of ARLEs benefits suffer from lack of experimental rigour, not having control groups that clearly isolate AR use as the experimental variable, if the studies have an experimental methodology at all.

Thus, the lack of definitive conclusions in literature regarding ARLE benefits, in terms of engagement benefits [5], [48], [54], [66], becomes understandable, as there are indications that ARLEs have positive effects on student engagement, but there is a lack of studies that explore this with rigor, with proper variable isolation, in an experimental approach [3], [12]–[17].

Taking into account the SCOLLAm context of being a pilot project for early primary school education [30], in order to validate the developed model and tooling, it was necessary to set up a series of experiments compliant with the identified issues (i.e. utilizing the tooling of the platform to enable isolation of AR use in the learning experience) and having proper experimental methodologies applied (i.e. clear hypotheses, experimental and control groups).

Due to the complexity of examining engagement in early primary school, as examined in chapters 4 and 5, and thus the need to develop the ARLEO instrument, validation of ARLEO in practice was needed. In order to set up the appropriate hypotheses, the full theoretical underpinnings of ARLEO, as well as of the model presented in the previous chapter on the basis of which the experimental tooling was developed, must be taken into account (Fig. 7.1).

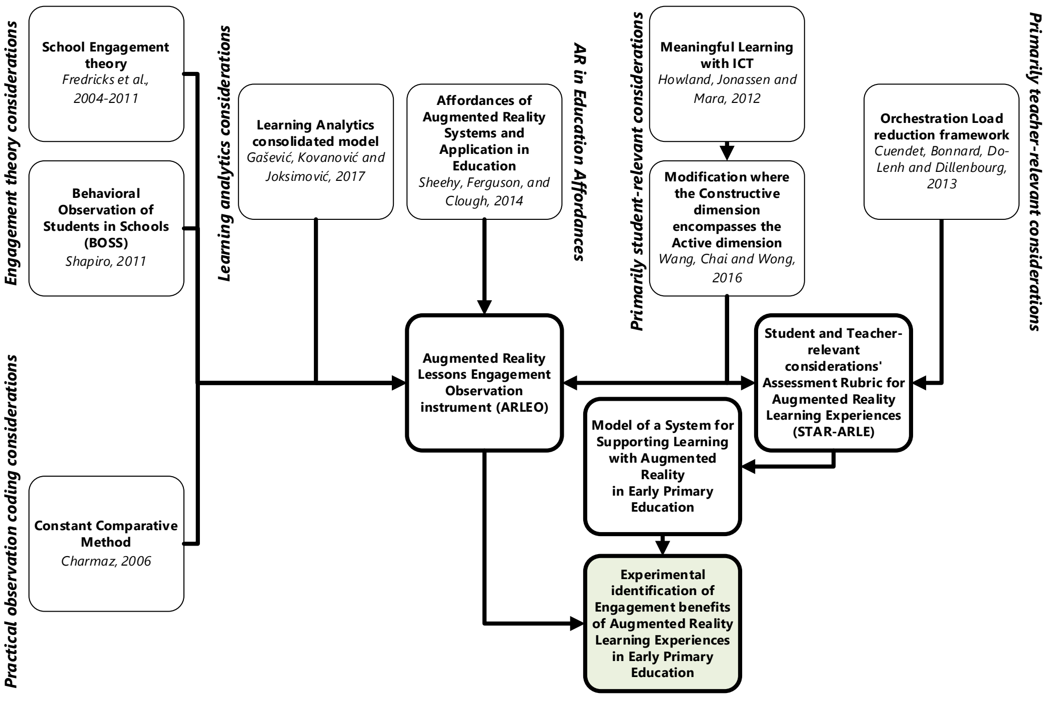

Fig. 7.1. Theoretical underpinnings of ARLEO and the model serving as basis for the experiments presented. Expanded from Fig. 1 in [21].

The hypotheses to be investigated therefore were:

- In early primary school education, it is possible to develop valid observational instruments for examining student engagement that are grounded in both engagement, ARLE theory and based on learning analytics.
- The application of ARLEs affects early primary school student engagement and constructive actions.

The proof of the first hypotheses would entail the following:

- The use ARLEO to encode student actions during ARLE lessons up to periodic coding,
- Statistical analysis, in line with learning analytics approaches, with statistically valid results,
- The development of a timeline overview of student actions during the lesson utilizing ARLEO coding,
- Such overview shows student engagement consistent with inherent assumptions about engagement, namely:
  - Constructive (cognitive, emotional, and behavioural) engagement and underlying actions start high and decrease over time,
  - Non-engagement starts low and increases over time; separately measured on basis of non-engagement coded student actions, it generally follows inversely aggregate engagement (i.e., at least one of the constructive engagement categories).

The proof of the second hypotheses would occur should the deployed ARLEs show a statistically significant difference in constructive engagement between the experimental and the control groups.

7.2.Tools and methods

The experiments were conducted by researchers and teachers at the partner primary school through joint co-design of the lessons into which ARLEs were to be included, to ensure tight integration of the ARLEs with the curriculum and lesson plan, giving the teachers the ability to slot in the ARLEs and digital lessons appropriately instead of traditional lessons.

For the study, two AR modules were designed, deployed as part of 5 in-class lessons in 2016 (during DBR development) and 4 in-class lessons in 2017 (during experimental work) for which data was collected, as well as 5 demonstration sessions for which data was not collected besides allowing teachers to observe student use of the ARLEs.

The lessons were from two courses: Mathematics and Nature and Society, identified through discussion with teachers as the most appropriate for augmentation. The 2nd grade Mathematics course (in the summer semester) has as one of the main lines of learning the learning of basic arithmetic (addition, subtraction, multiplication, and division) up to 100, with the numbers to be used in those operations being increased throughout the year, which was selected to be utilized for the ARLE experiments via the ARLE module AR.Math. AR.Math is intended as a student work desk ARLE, where simple mathematics problems are solved by showing the tablet (anthropomorphised through questions seeming to come from the “friendly smart owl” who is helping the student learn) the result via paper markers (Fig. 7.2).

Fig. 7.2. A student using AR.Math: top - the student scanning a marker during the addition lesson; bottom - the student viewing the task through the device. Adapted from [134].

In the Nature and Society curriculum for the 2nd grade, Means of Transport and Recycling lessons were selected for augmentation during the experiments via ARLE module AR.Curious. The additional demonstration sessions were based on the above lessons utilizing the AR.Curious module for the embedded ARLE experience, with an additional ARLE being developed to cover the subject matter of important historical persons of Zagreb, Croatia in the 19th century and of common animals and the terminology associated with them. Questions regarding those topics are answered by finding the correct answer within the classroom, where models of answers were presented with markers attached to them (Fig. 7.3).

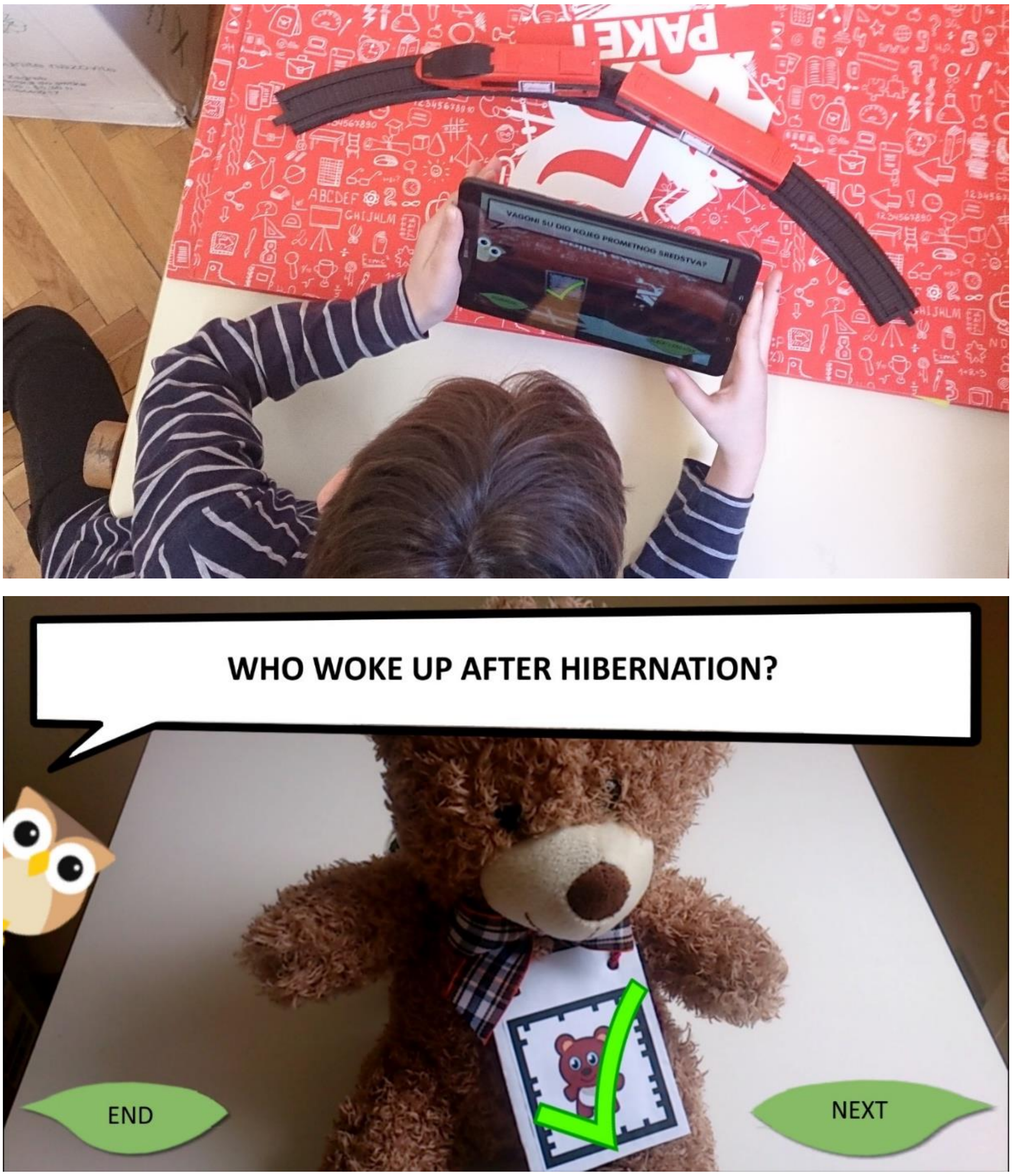

Fig. 7.3. A student using AR.Curious: top - student scanning the marker on a lesson object during the means of transport lesson; bottom – a task being solved in the animals' lesson, as seen by a student on the device during the lesson. Adapted from [134].

The classes during which data was collected were two classes of the same generation, being the first grade in 2016 and who became second grade in 2017 of the partner urban primary school in Zagreb, Croatia (ages 6-8). Additional demo sessions were held in generation adjacent classes (1st and 3rd grade).

The 2017 experimental study was conducted with one class (2B – 15 students) being designated as the experimental class, and one class (2A – 18 students) being designated as the control class. Students in both classes had previous experience from their time in the first grade with tablet lesson use, for both classic digital lessons as well as ARLEs, as part of the DBR development efforts for AR capabilities as well as due to other SCOLLAm efforts, mitigating any novelty factor concerns. To ensure background equivalence of the two groups, a pre-study check was performed with teachers providing their subjective scoring of students in terms of academics, engagement, socio-economic background, work habits and family support. Analysis of the data did not reveal significant differences in the populations of the two classes.

The approach taken was 1:1 deployment of tablets to students, with the tablets not being permanently assigned to students, requiring distribution at the beginning of each lesson where tablets are used. Each experience was tailored to take up the length of a school hour (45 minutes), including set-up (tablet distribution, set-up of filming equipment etc.), instruction on the use of the ARLE, reading the digital lesson slides bookending the ARLEs, performing the ARLEs (10 min or somewhat more of active use), follow-up of the ARLE and lesson clean-up (collection of tablets, dismantling of filming equipment, etc.)

In terms of lesson content approach, the lessons were developed utilizing the Author digital lesson designer tool, part of the SCOLLAm system. The lessons were designed with several slides of intro material reviewing the topic of the lesson followed by a slide hosting either the ARLE widget or a HTML5 widget (as conceptually depicted in Fig. 6.4), that would launch the associated experimental or control experience, both of which would be parametrized to present the same interactive lesson contents (with the obvious differentiation of the presentation methodology, as can be observed in Fig. 7.4), with the lesson concluding with several finishing up slides summarizing the activity.

With regards to the interactive experience, whether AR or HTML5 based, in both cases students could freely move from the intro slides, through the experience and through the finishing slides. In both cases students would be given a sequence of five randomized (in case of the AR.Curious and equivalent HTML5 modules) or randomly generated (in case of the AR.Math and equivalent HTML5 modules) questions, one after another, whereupon they would have a choice to either start another sequence of 5 questions or to stop and finish the lesson.

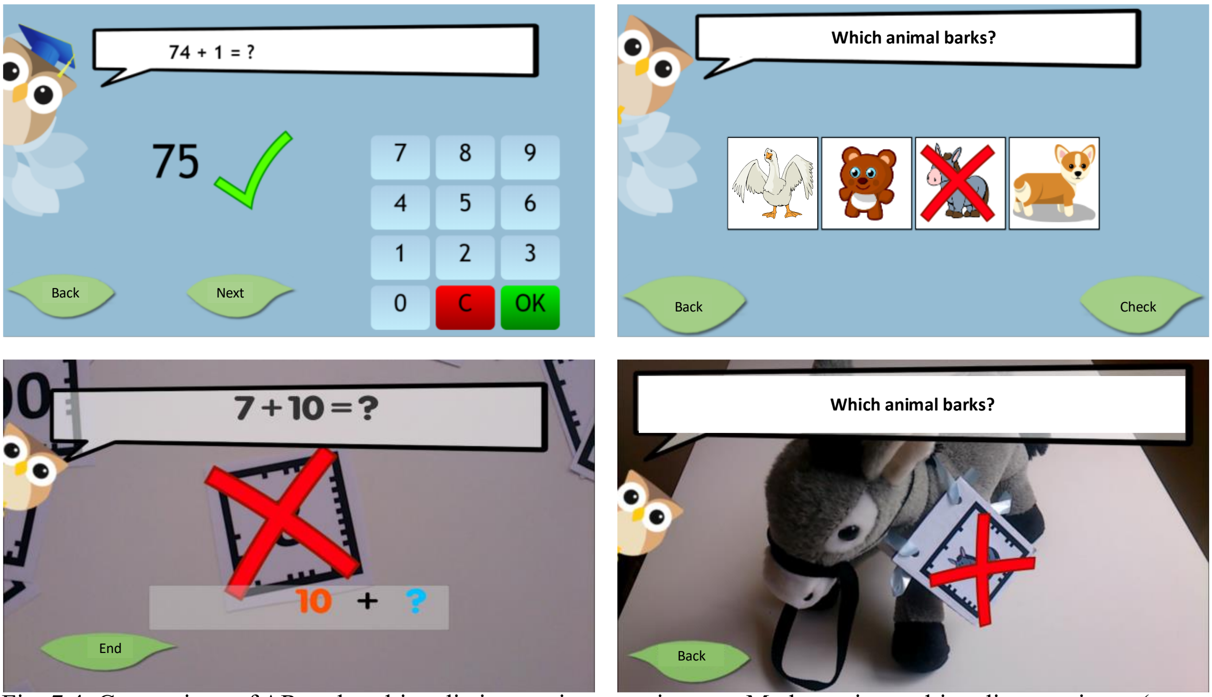

Fig. 7.4. Comparison of AR and multimedia interactive experiences - Mathematics multimedia experience (upper left) where students enter the result via keypad, Mathematics AR experience (lower left) where students enter the result via real-world paper markers, Nature and Society multimedia experience (upper right) where results are chosen via multiple choice and Nature and Society AR experience (lower right) where students enter the result via identifying the object. Note: screenshots translated to English. Originally published as Figure 3 in [132].

The intentional parallelism of the approaches to isolate AR as the experimental variable persists in the ARLE module and the HTML5 content architecture – they utilize the same APIs (web services) to get the lesson contents and log student activities.

Data collection was conducted by video-recording the lessons, with the recordings reviewed and student actions coded, in line with the ARLEO methodology presented in chapter 5. In addition, researchers kept observation logs. Following initial review of observation logs and recordings, as well as coordination between researchers, student focus groups were held as well as teacher interviews. Student focus groups were conducted by interviewing students in groups of 6, with the entire experimental and control population interviewed. Students were asked questions from a pre-prepared interview script constructed based on researcher observations, initial recording review and researcher consultations. The script was constructed to gain contextualization of phenomena observed as well as to get a global picture of engagement with ARLE and control content from the students' point of view. Finally, at the end of the semester, participating teachers were interviewed during an end of project away day. While researchers prepared notes based on observations, recordings review and analysis of student focus group responses, said interviews were conducted in a semi-structured format, in order to allow teachers to express their full opinions of the interventions done during the semester.

Consequently, the results of the student focus groups and teacher interviews are thus used in order to contextualize the discussion in the following chapter.

7.3. Results of experimental observation of engagement

The results of the 2017 experimental studies are presented in this section. In 2017, final versions of the AR.Math and AR.Curious ARLEs were deployed two times during Mathematics and Nature and Society lessons, respectively. Through AR.Math, students had an opportunity to practice basic arithmetic operations (addition, subtraction, multiplication, and division) up to the level of number complexity they had achieved up to the point of the deployment of the lesson. With AR.Curious, two lessons were tackled – a lesson on recycling and a means of transport lesson.

Coding of student actions was done based on the first 10 minutes of AR use (or first 10 minutes of answering digital lesson multiple choice questions for the non-AR group) to achieve comparable results. Table 7.1 presents the results of the initial coding per the ARLEO process flow (see section 5.2) and algorithms (in particular Algorithm 5.1 as part of the overall flow described by Algorithm 5.5) i.e., the dynamic catalogue of initial codes developed based on the recordings of the 2017 lessons (both AR and non-AR). Focused coding was performed on those codes via Algorithm 5.2 developing the focused codes in Table 7.2, which were assigned to related categories of engagement via axial coding utilizing Algorithm 5.3. Based on such coding, period coding was performed per Algorithm 5.4. Each period was 15 seconds long. The results of period coding are presented in aggregated graph fashion (i.e., all results combined for both lessons of the ARLE for the experimental deployments) for AR.Curious and AR.Math in Fig. 7.5 and Fig. 7.6, respectively, for reference.

In the reminder of this section the results from the experiments during the 4 lessons are presented, with both the results in the experimental class (receiving the ARLE) and the results in the control class (receiving the non-AR digital lesson equivalent control experience) are presented (i.e., the coding was done for 8 lessons total). Class 2A was used as the control class, while class 2B was the experimental class.

Based on ARLEO periodic coding, for each lesson it was possible to determine how many students displayed a certain category of engagement for each 15s period of the 10 minutes of the experience (40 periods in total).

Due to the relatively low number of students in each class (18 students in 2A and 15 students in 2B), prior to further data analysis using statistical methodologies, a hypothesis of normality needed to be checked. This was done using the Shapiro-Wilk normality test [146] as the most appropriate due to the small sample size. It was applied to all 5 categories of engagement (as encoded for periods by periodic coding per Algorithm 5.4 as part of the overall flow per Algorithm 5.5), as the variables under observation, in both the experimental and control classes.

The check resulted in findings of non-normal distribution in the 2A control class for behavioural engagement during all four lessons and emotional engagement during the Nature and Society lessons. For the 2B experimental class, non-normal distribution was found for behavioural engagement in the first Mathematics lesson, non-engagement, and aggregated engagement for the second Mathematics lesson, as well as behavioural, emotional, and aggregated engagement for the Means of Transport lesson.

As utilizing common statistical tests such as the t-test would be affected by the non-normal distribution, for variables with non-normal distribution the Mann-Whitney U test [147] had to be used, as a test that is non-sensitive to non-normal distribution data.

TABLE 7.1

INITIAL CODES FOR STUDENT ACTIONS OBSERVED DURING THE 2017 STUDY

Adapted from Table 2 in [134]

Actions / Initial Codes	
Announcing / bragging	Looking at whiteboard
Annoyed	Looking for answers
Asking for teacher assistance	Looking for objective
Assistance from researcher	Looking up multiplication table
Assistance from researcher (non-engaged)	Manipulating task object
Being asked to look at results	Next cycle discussion with researcher
Being bothered by classmate	Not solving
Bored	Observing another student's work
Bragging	Observing discussion
Bumped into another student	Observing teachers
Chatting	Physically playing around with the tablet
Chatting and moving around	Picking nose
Checking himself over	Playing
Cleaning tablet	Playing around
Climbing to position to solve problem	Playing around with classmate
Comparing solutions with another	Playing around with pen
Complaining ("Not again")	Playing around with the tablet
Confrontation	Playing on tablet
Confused	Playing with classmate
Determining boundary	Playing with tablet
Discussing problem with classmate	Pointing out something to classmate
Discussing results with another student	Preparing
Discussing solution with another student	Putting on glasses per teacher instruction
Discussing with classmate	Reading
Discussing with researcher	Reading carefully
Discussing with researcher / finished / go-again	Receiving classmate assistance
Discussing with teacher	Researcher intervention (cheating)
Discussion with researcher	Returned tablet
Distracted	Running to objective
Distracted by bottle	Scanning all markers
Distracted by discussion	Scratching herself
Distracted by photography session	Showing non-lesson to classmate
Distracted reading	Showing results to classmate
Drinking juice	Sitting down to get better view of objective
Drinking water	Solving
Exclamation "YES"	Solving carefully
Fiddling with clothes	Solving problem with colleague assistance
Fidgeting	Solving while listening to researcher comments
Fidgeting and chatting	Solving with assistance from colleague
Finished / go-again discussion	Solving with assistance of assistant
Finished, asking for permission to stop	Solving with assistance of classmate
Fixing hair	Solving with assistant's assistance
Focused on work	Solving with classmate
Frustrated	Solving with help of assistant
Getting assistance from classmate	Solving with help of colleague
Going to objective	Stopped solving
Going to researcher for help	Stretching
Going to researcher to claim completion	Tablet returned
Going to teacher / finished / go again	Taking bottle
Going to teacher for help	Taking selfies on tablet
Going to teacher for instruction	Talking to another far away student
Going to teacher for permission to stop	Talking with teacher
Happy	Teacher intervention (non-engaged)
Helping a colleague	Technical issues
Jumping to answer	Telling a joke to another
Kneeling to get answer	Thinking
Left classroom	Thinking while jumping
Listening to instructions	Tripping over bag
Looking around the class	Trying answers at random
Looking at another student's tablet (no lesson)	Walk around the classroom (non-task)
Looking at another's lesson	Wandering around
Looking at images	Waving outside
Looking at the blackboard	Working

TABLE 7.2
FOCUSED CODES WITH ENGAGEMENT CATEGORIZATION
Adapted from Table 3 in [134]

Focused Code	Behavioural Engagement	Emotional Engagement	Cognitive Engagement	Aggregated Engagement	Non-Engagement
Assistant-student task cooperation	-	O	O	O	-
Cheating req. intervention	-	-	-	-	O
Classmate conflict	-	-	-	-	O
Classmate task cooperation	-	O	O	O	-
External distraction	-	-	-	-	O
Interaction with authority figure	-	O	-	O	-
Non-task chatting	-	-	-	-	O
Non-task fidgeting	-	-	-	-	O
Non-task looking around	-	-	-	-	O
Non-task misc. action	-	-	-	-	O
Non-task movement	-	-	-	-	O
Non-task play	-	-	-	-	O
Passive while being assisted	-	O	-	O	-
Social task results sharing	-	O	O	O	-
Stopping work on task	-	-	-	-	O
Task boredom / annoyance	-	-	-	-	O
Task confusion	-	-	-	-	O
Task movement	O	-	O	O	-
Task-based happiness	O	-	-	O	-
Task-oriented exploration	O	-	O	O	-
Task-oriented work	-	-	O	O	-
Working while listening to teacher	-	O	O	O	-

O – focused code is a subcategory of the engagement category
- – focused code is not a subcategory of the engagement category

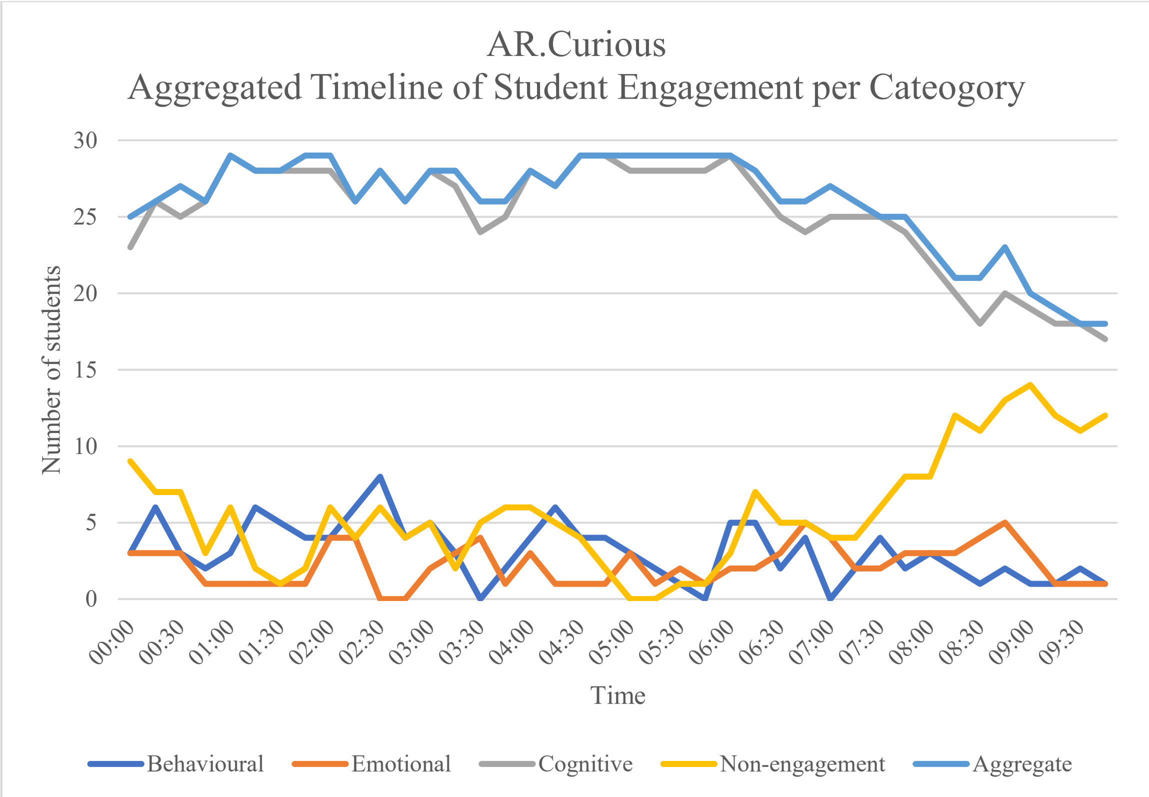

Fig. 7.5 Engagement categories periodic timeline during AR.Curious ARLEs in 2017 (aggregated). Developed for [134].

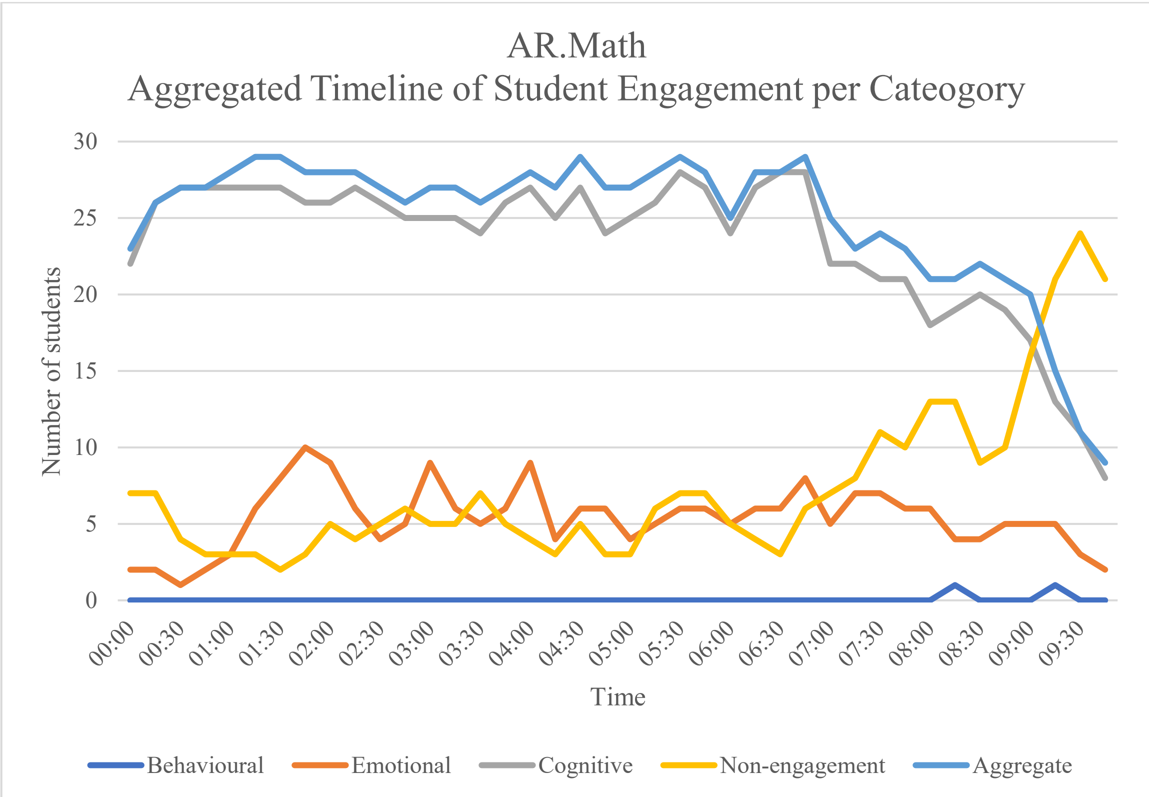

Fig. 7.6 Engagement categories periodic timeline during AR.Math ARLEs in 2017 (aggregated). Developed for [134].

7.3.1. The Recycling Lesson

The Recycling Lesson is a lesson in the Nature and Society curriculum during which students are taught and/or reminded of the importance of separating and properly recycling household waste. In this context, they are taught about the use of different bins for recycling of different types of recyclable waste, such as paper, empty plastic containers, etc.

In the ARLE as part of the lesson, various types of bins (for plastics, for paper, for metal and for glass) were placed around the classroom, with the students being instructed to scan the marker on the bin that is correct for recycling the item they are asked on the tablet to recycle. The control group non-AR experience consisted of the same questions on the need to identify the proper bin for the item asked about, with the potential bins being provided as images, potential answers in a multiple-choice answer selection. See Fig. 7.4 for reference.

Applying the t-test to the periodic coding of the lesson, statistically significant higher number of periods of cognitive, behavioural, and aggregate engagement can be observed in the experimental class, while statistically significant higher number of periods of non-engagement can be observed in the control class, as presented in Table 7.3.

TABLE 7.3
T-TEST COMPARISON OF THE EXPERIMENTAL AND CONTROL CLASS – RECYCLING LESSON
Adapted from Table 2 in [132]

Variable	Mean difference
Recycling Cognitive	6.389*
Recycling Behavioural	4.913**
Recycling Emotional	1.452
Recycling Non-engagement	-10.214*
Recycling Aggregated	7.032*

Statistically significant results are indicated by italics and underline.
*p<0.05, **p<0.001

Analysing the patterns of engagement over time (as presented graphically in Fig. 7.7 and Fig. 7.8), it can be observed that aggregate engagement (and cognitive engagement as the major contributor to aggregate engagement) has a specific pattern in the lesson, with high engagement at first, followed by a drop as a first group of students disengage, stabilization for a period of time, followed by a second drop or collapse of engagement towards the end of the lesson.

While both the experimental and control class follow this pattern, the timing is different, with the first drop occurring significantly later for the experimental class (at approx. 6:30 for the experimental class and at approx. 4:00 for the control class), indicating a longer period of high class-wide student engagement. The second drop of engagement happens at a similar time for both classes (at approx. 8:00).

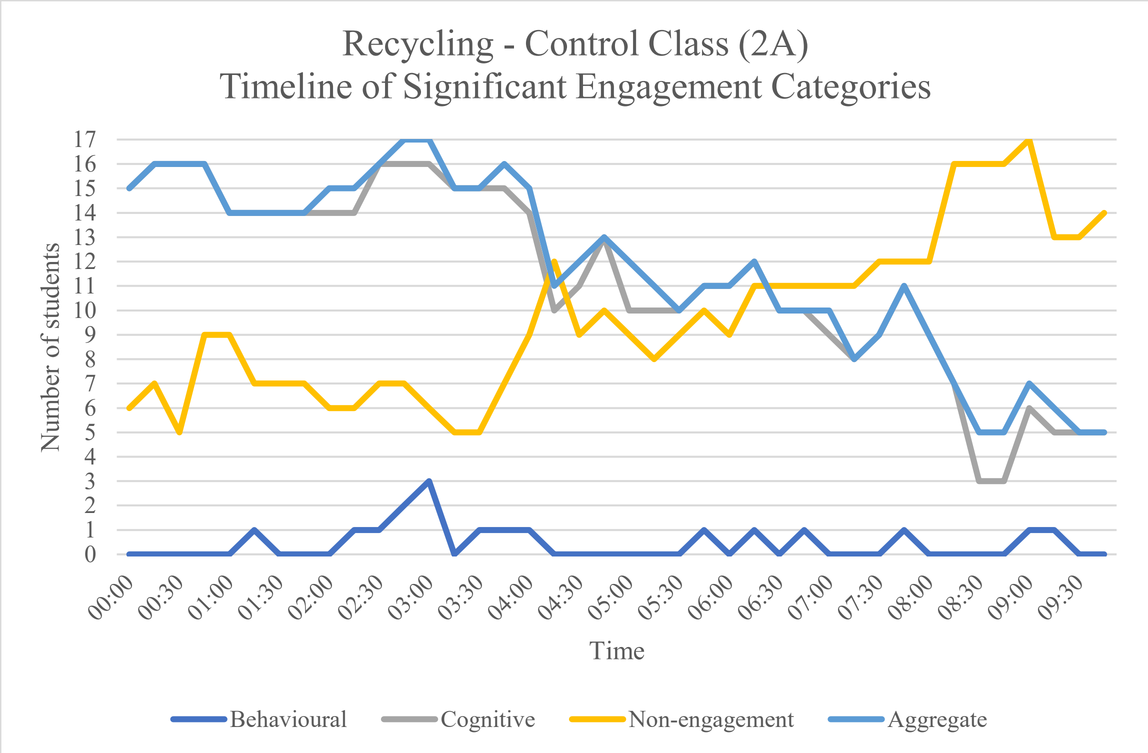

Fig. 7.7. Timelines of significant engagement categories during the Recycling lesson for the control class. Originally published as part of Figure 7 in [132].

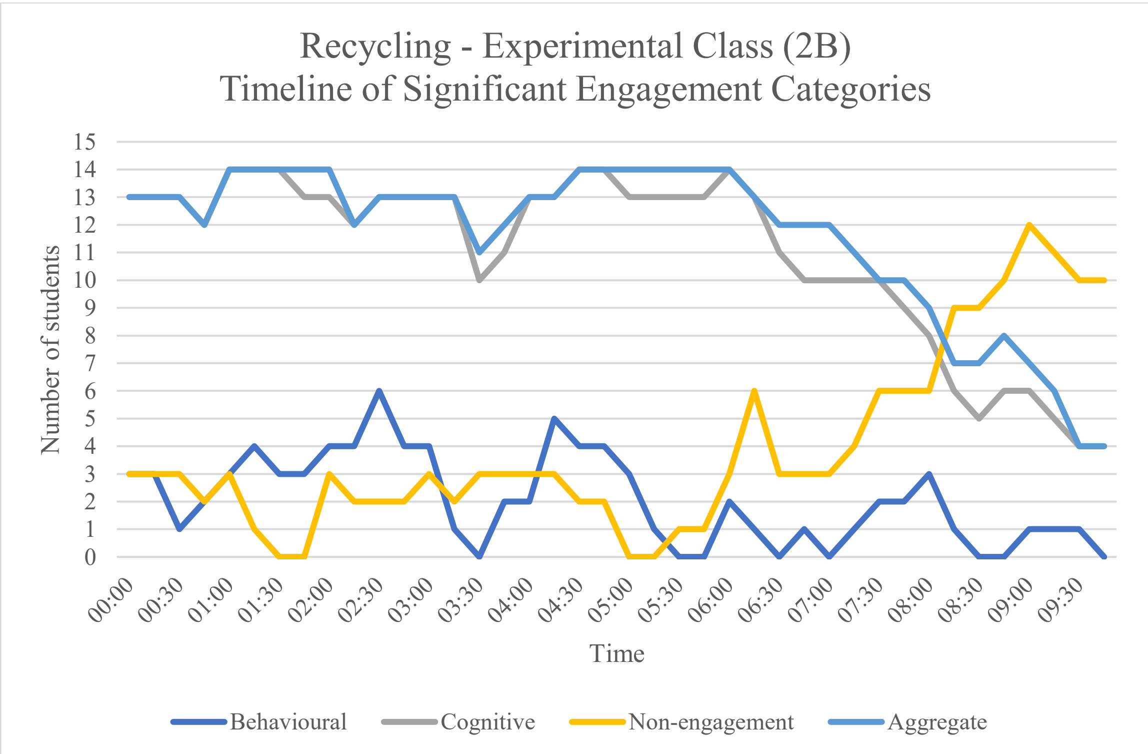

Fig. 7.8. Timelines of significant engagement categories during the Recycling lesson for the experimental class.

Originally published as part of Figure 7 in [132].

Behavioural engagement follows a similar pattern of higher engagement during the first half of the experience in both the experimental and control classes. However, consistently throughout the experience, more students in the experimental class were behaviourally engaged.

In terms of statistical significance versus distribution, behavioural engagement was not normally distributed, but the statistical significance of the result was confirmed via the Mann-Whitney U tests. Emotional engagement did not have a statistically significant difference – in both classes there were several student-teacher and student-student constructive and emotionally engaging conversations.

7.3.2. The Means of Transport Lesson

The Means of Transport Lesson is a mid-semester lesson in the Nature and Society curriculum during which students learn about the various means of transport, for what purpose is each used for and the associated terminology of the means of transport and the associated infrastructure.

The ARLE part of the lesson was constructed as a question-and-answer session where students needed to identify the correct means of transport to which a statement posed in the question applied. In the experimental class, this was done via positioning of multiple models (car, bus, plane, train, and ship) around the classroom and asking students to identify with their tablet the correct one to answer the question. In the control class, the possible answers were presented as pictorial multiple-choice options (see Fig. 7.4 for reference).

The results of analysis of the engagement of the students are generally consistent with the ones in the Recycling lesson (compare Table 7.4 with Table 7.3).

TABLE 7.4
T-TEST COMPARISON OF THE EXPERIMENTAL AND CONTROL CLASS – MEANS OF TRANSPORT LESSON
Adapted from Table 3 in [132]

Variable	**Mean difference**
Transport Cognitive	10.167**
Transport Behavioural	2.589*
Transport Emotional	-1.178
Transport Non-engagement	-8.822**
Transport Aggregated	9.444**

Statistically significant results are indicated by italics and underline.

*p<0.05, **p<0.001

Similar timeline trends to the Recycling lesson can also be observed (Fig. 7.10 and Fig. 7.11), with similar grouping patterns of cognitive, aggregate, and non-engagement.

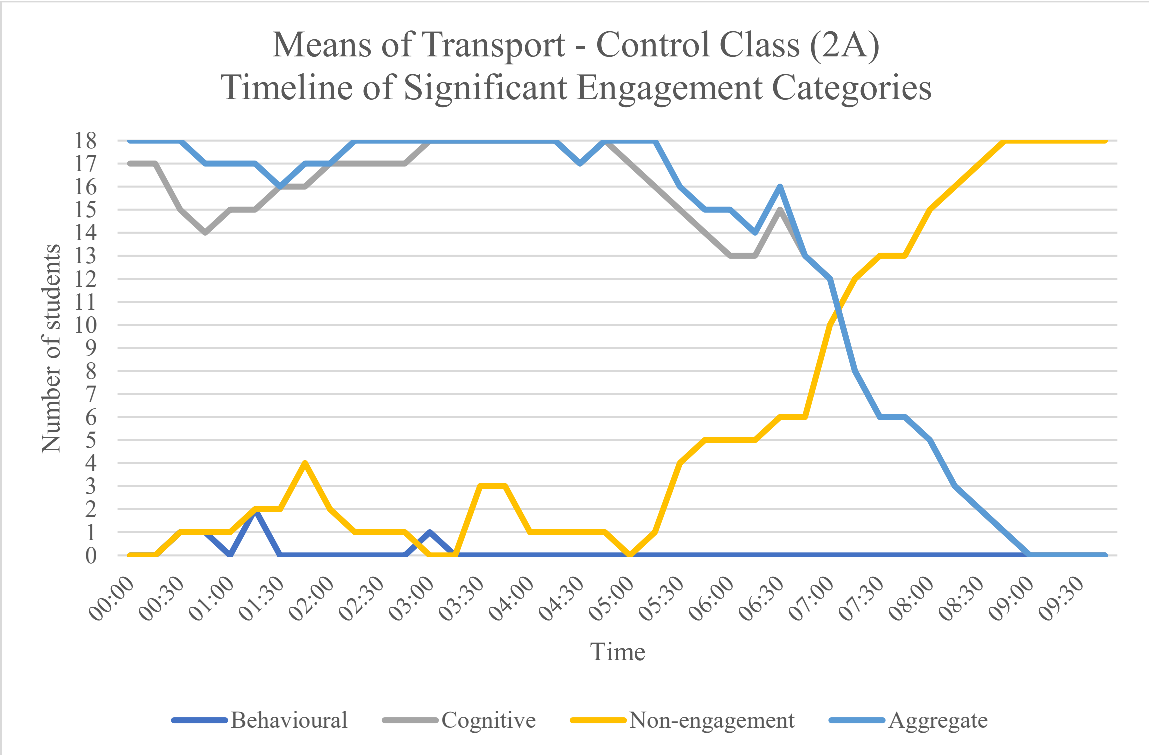

Fig. 7.9. Timelines of significant engagement categories during the Means of Transport lesson for the control class. Originally published as part of Figure 8 in [132].

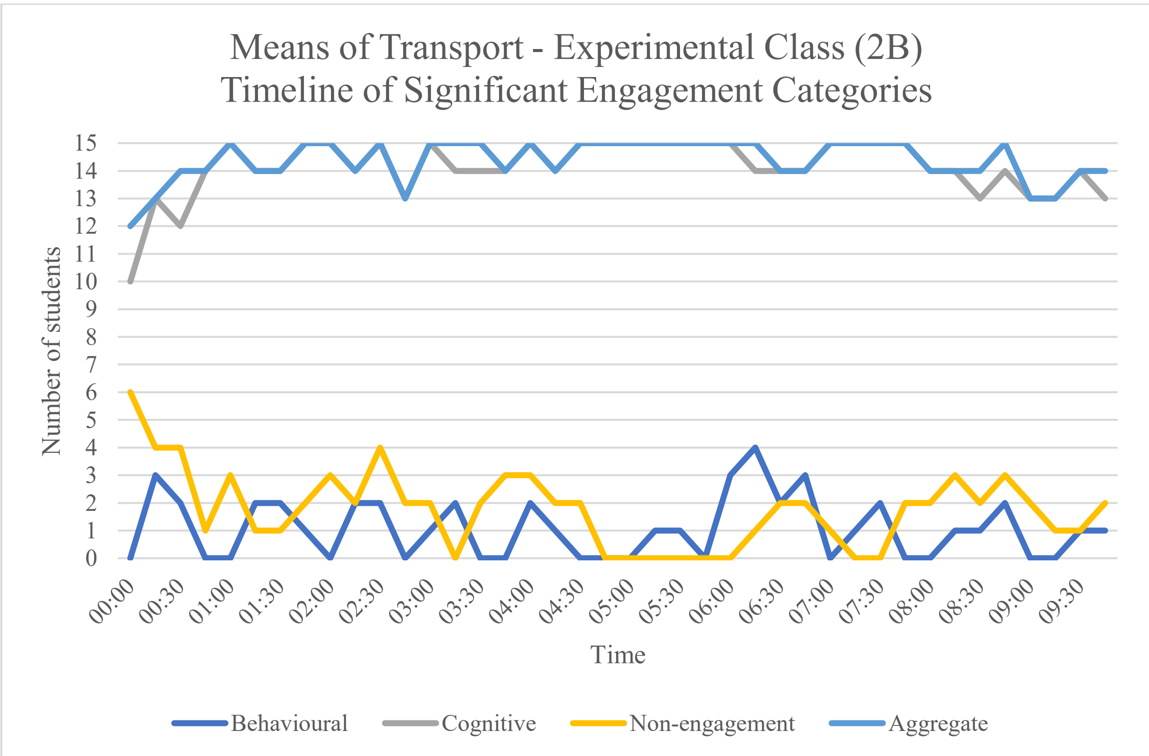

Fig. 7.10. Timelines of significant engagement categories during the Means of Transport lesson for the experimental class. Originally published as part of Figure 8 in [132].

There is a difference in that there is only one drop-off of cognitive and aggregate engagement, beginning at 5:00 for the control group and leading to a full disengagement by 9:00. In contrast, for the experimental group those engagement categories remain high during the 10-minute observation window.

In terms of distribution, behavioural and aggregated engagement was not normally distributed, but the significance of the results was confirmed via Mann-Whitney U tests. Emotional engagement follows a similar pattern to the one in the Recycling lesson, being similar in both the experimental and control classes and not being normally distributed.

7.3.3. The First Mathematics Lesson

The First Mathematics Lesson was held in mid-part of the summer semester as part of the Mathematics curriculum. At that point, students had covered addition and subtraction of natural numbers of up to 100 as well as multiplication and division with 1 and 2 where the result is a natural number up to 100. The experience was configured accordingly, to pose math problems - addition, subtraction, multiplication, or division of two numbers within the covered ranges.

In the ARLE, experimental class students replied to the posed questions by assembling the reply via number markers on pieces of paper. In the digital experience control class, students replied by entering the result via a keypad. See Fig. 7.4 for reference. Statistical analysis of the periodic coding for the lesson shows statistically significant differences in cognitive, aggregated, and non-engagement, as can be observed in Table 7.5.

TABLE 7.5
T-TEST COMPARISON OF THE EXPERIMENTAL AND CONTROL CLASS – FIRST MATH. LESSON
Adapted from Table 4 in [132]

Variable	**Mean difference**
Math 1 Cognitive	7.165*
Math 1 Behavioural	-0.161
Math 1 Emotional	3.784
Math 1 Non-engagement	-10.612**
Math 1 Aggregated	7.671*

Statistically significant results are indicated by italics and underline.

*p<0.05, **p<0.001

Both the experimental and control class show the same pattern of cognitive engagement, with an early high engagement period, a mid-experience disengagement for several students and a final class-wide disengagement towards the end. The difference is the latter occurrence for the experimental class, with the mid-experience drop beginning at 5:30 vs 2:30 for the control, as well as the final collapse beginning at 8:45 vs 8:15 for the control (Fig. 7.11).

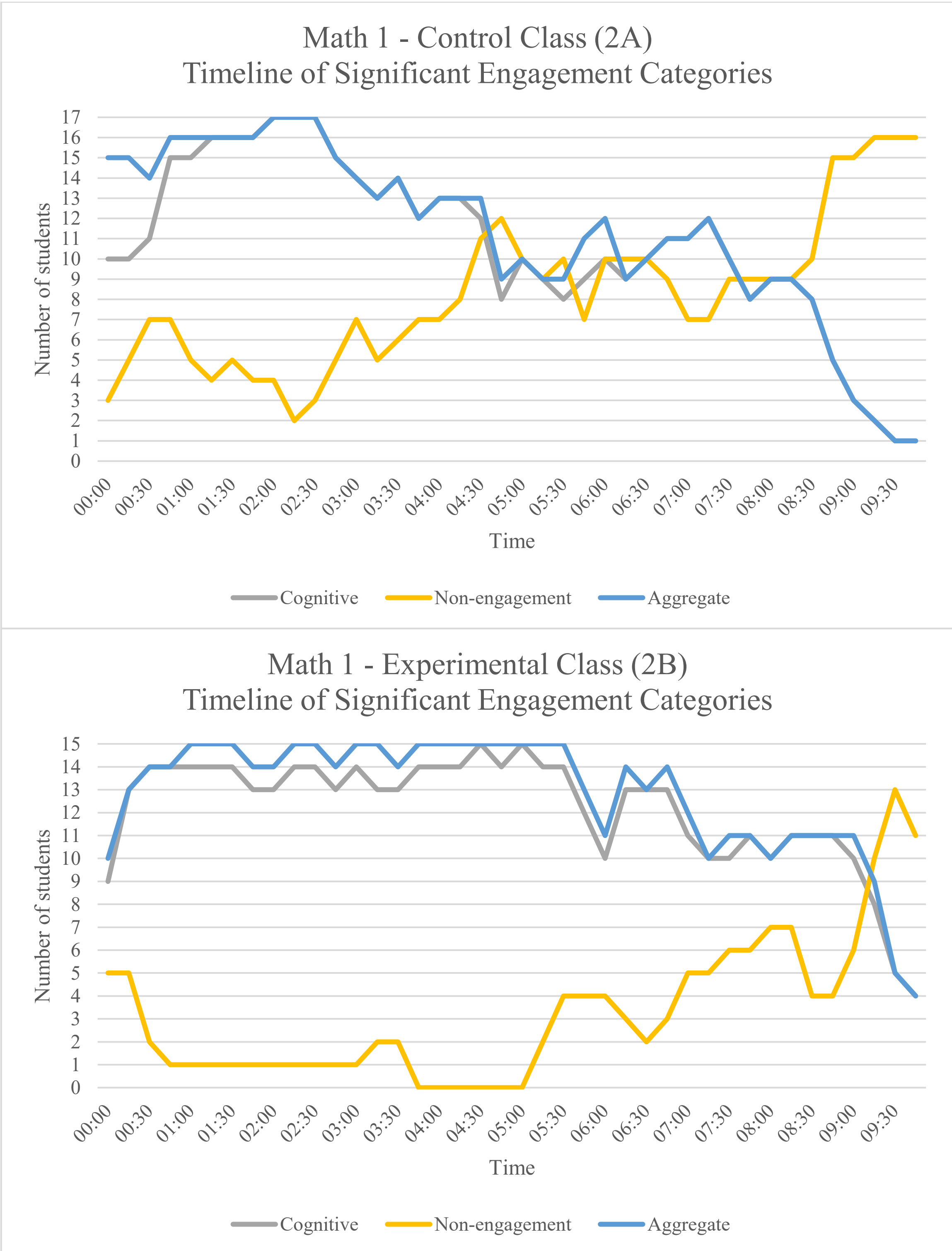

Fig. 7.11. Timelines of significant engagement categories during the first Mathematics lesson for the control class (top) and experimental class (bottom). Originally published as Figure 9 in [132].

Like the Nature and Society lessons, in the first Mathematics lesson we can observe that the aggregate engagement essentially follows the pattern of cognitive engagement, showing that it is the dominant engagement category during the lesson, with behavioural and emotional engagement being at significantly lower levels in both the experimental and control class (and with non-statistically significant differences in the case of the first Mathematics lesson).

With non-engagement being measured separately (i.e., based on non-engagement actions, as identified via associated initial and focused codes) to engagement categories contributing to aggregate engagement, the inverse relationship between aggregate engagement and non-engagement contributes to the validity of the ARLEO model as those separately measured variables are behaving in line with expectation (essentially inverse values).

7.3.4. The Second Mathematics Lesson

The second mathematics lesson was held two months after the first, as a repetition training lesson for math problem solving. During that time students progressed with their lessons to the point of utilizing addition and subtraction of natural numbers up to 100 as well as multiplication and division of natural numbers with numbers between 1 and 7, with the result being up to 100. The experience was therefore adjusted to that scoping. Otherwise, the lesson set-up remained the same in terms of the tools and methods used vis a vis the experimental and control classes.

The results are atypical compared to other lessons, as can be observed in Table 7.6. Cognitive and aggregated engagement have non-significant differences between the experimental and control classes (the aggregated engagement values, as analysed before, being mostly affected by cognitive engagement), while there is a statistically significant difference in behavioural engagement in favour of the control class. Only non-engagement follows the pattern set in having a statistically significant difference in favour of the experimental class.

TABLE 7.6
T-TEST COMPARISON OF THE EXPERIMENTAL AND CONTROL CLASS – SECOND MATH. LESSON
Adapted from Table 5 in [132]

Variable	**Mean difference**
Math 2 Cognitive	2.878
Math 2 Behavioural	-4.333*
Math 2 Emotional	-1.733
Math 2 Non-engagement	-6.100*
Math 2 Aggregated	3.644

Statistically significant results are indicated by italics and underline.

*p<0.05

The behavioural differences can be traced back to a few students being behaviourally engaged during most of the 10-minute observation window in the control class, while there were no behavioural engagement actions, as coded via initial and focused codes, observed in the experimental class, as can be observed in Fig. 7.12. This anomaly is further explored in the discussion.

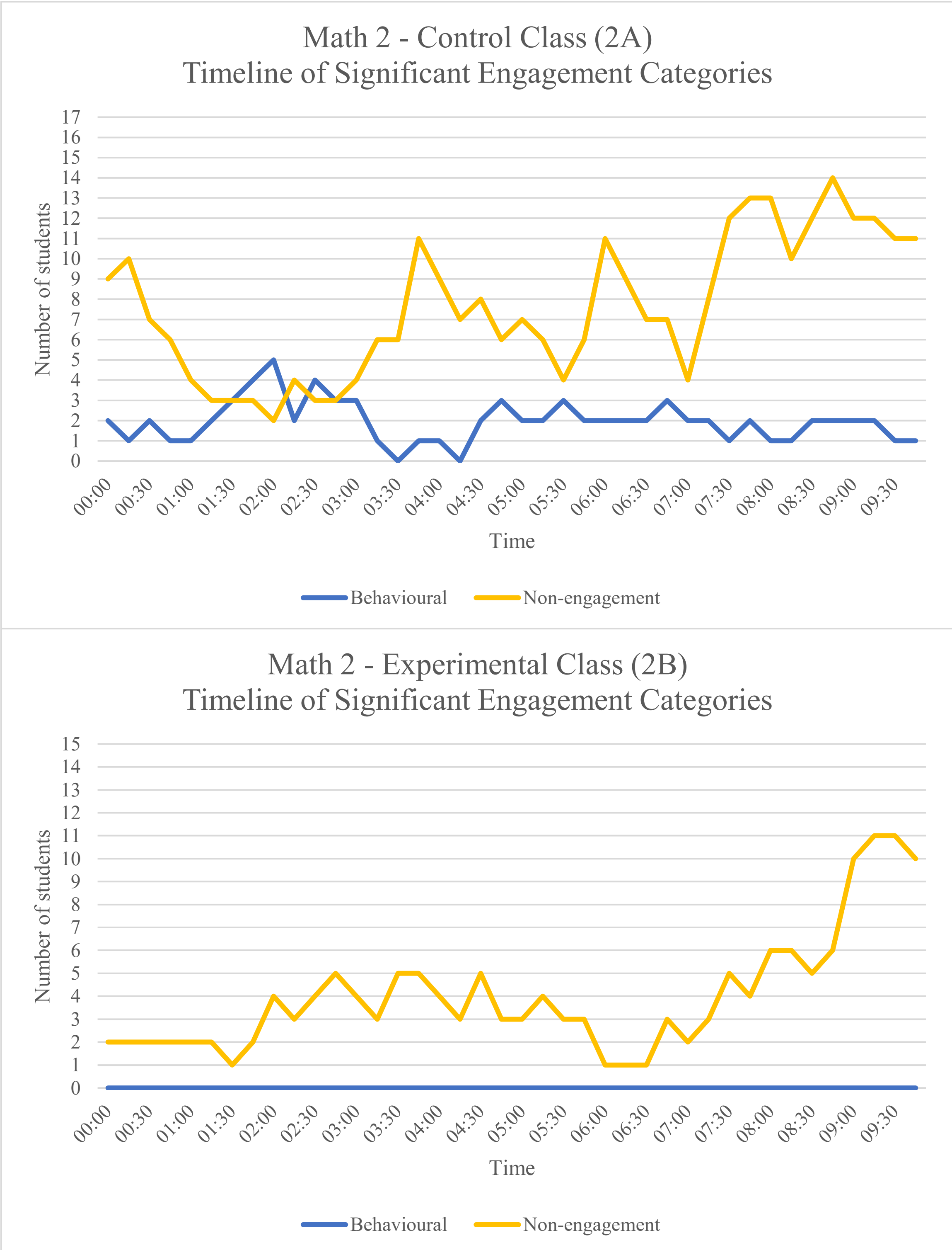

Fig. 7.12. Timelines of significant engagement categories during the second Mathematics lesson for the control class (top) and experimental class (bottom). Originally published as Figure 10 in [132].

Non-engagement, while having a statistically significant difference between the experimental and control classes in favour of the experimental class, in line with patterns observed with other lessons, has, in the case of the second Mathematics lesson, the by far smallest difference amongst the lessons. It does, however, follow the pattern of the other lessons in having a later growth in the experimental class versus the control.

Due to the non-normal distribution of the behavioural and non-engagement data, Mann-Whitney U tests were performed and have confirmed the significant difference between the experimental and control group data for those engagement types.

8. DISCUSSION

Based on the results presented in previous chapters, in this chapter those results are discussed, and implications analysed. First, STAR-ARLE the results of the application of STAR-ARLE are analysed and then broader conclusions out of those results discussed. Secondly ARLEO is examined, first analysing the implications of the results of the experiments, followed by an examination of the implications of ARLEO as an instrument. Finally, an assessment is conducted regarding the SCOLLAm tooling implemented versus the theoretical model presented in chapter 6, including a STAR-ARLE self-assessment, examining as well possible ways to cover the gaps identified. Following those discussions, limitations of the conducted studies and developed frameworks are explored for STAR-ARLE and ARLEO. At the end of the chapter, potential directions for future work are presented.

8.1. STAR-ARLE – findings regarding specific metrics for techno-pedagogical maturity of learning with augmented reality

8.1.1. Correlation and maturity analysis

Examining the findings presented in section 3.5, regarding the correlation analysis presented in section 3.5.3, the following observations and conclusions are identified.

Firstly, a negative correlation can be observed between the constructive and minimalism dimensions, indicating tensions between those affordances in providing a constructive meaningful learning experience for students while maintaining a minimalistic user experience which assists teachers with orchestration load. On the other hand, the constructive dimension is in correlation with the awareness dimension as well as with the cooperative dimension. Taken together, this indicates that as the pedagogy becomes more complex (i.e., more constructive) more thought is given to teacher affordances regarding awareness as well as making the experience more cooperative to increase the meaningfulness for students. At the same time, such a more complex pedagogy requiring higher affordances also affects the user experience, which is not able to be maintained in the minimalist fashion, at least in the ARLEs reviewed.

I.e., there appears to be a trend splitting ARLEs into two groupings. The first grouping of ARLEs is simpler, minimalist, not very constructive, low affordance with regards to awareness and cooperation ARLEs. The second grouping of ARLEs are more complex, cluttered ARLEs but which are more constructive and cooperative, as well as having higher awareness affordances. In this regard, the correlation of the authentic dimension with constructive and cooperative ones is a finding of interest - ARLEs by their nature tend to be at least somewhat authentic; this finding indicates that this typically goes hand in hand with having more constructive and cooperative design, leading to indications of this being a set of affordances considered together by lesson designers.

Focusing more on teacher affordances, two correlation trends are of interest. The first is the correlation of the intentional dimension with the empowerment and awareness dimensions. This is to be expected as the role of the teacher as facilitator assisting the student in identifying and resolving their learning issues within the intentional dimension goes hand in hand with them having effective affordances and orchestration headspace available to act in that role through more mature levels of empowerment and awareness. Similarly, the empowerment, awareness and flexibility dimensions correlate with each other, indicating that ARLE designers consider those affordances together. This must be contextualized with the low maturity of the orchestration load-related affordances in general, indicating that teacher concerns are in general not highly considered by ARLE designers, but when they are, the key dimensions of empowerment, awareness and flexibility are all tackled, indicating that it is key that ARLE designers consider teacher needs and involvement in their design process.

In terms of further findings, it is also important to note that a few ARLEs (in fact, during the review only *EULER* [121] was identified as being one) have facilities for digital cooperation and collaboration, with the rest depending on lesson design fostering collaboration in person in the real-world. The previously mentioned issue of the orchestration load dimensions having low maturity is as well important, indicating little consideration of teacher affordances in general ARLE design.

8.1.2. STAR-ARLE analysis conclusions

The findings show that affordances assisting students in having meaningful learning do tend to be considered, but with mixed results, with different ones emphasised depending on the type of ARLE. However, the maturity of affordances for assisting teachers in reducing their orchestration load tends to be low, with many ARLEs not taking teacher concerns into account at all, requiring this to be considered as a field for improvement in future efforts.

This has a consequence on any modelling work for systems to support ARLE application, as it indicates that such models must take teacher considerations more strongly in regard, as well as taking into consideration the correlation analysis results showing correlation clustering of the maturity of certain affordances.

That, of course, starts with involving teachers more in the actual design of the ARLE and working with them in a co-design and preferably iterative approach in developing appropriate ARLEs for their classroom, so that an ARLE is something that is a positive addition to the classroom instead of causing orchestration overload.

As well, an important consideration for any model is to incorporate a tool such as STAR-ARLE to allow for a self-assessment of offered affordances to support ARLE designers in determining where their ARLE is strong and where it is weak, and to make conscious decisions regarding the maturity in certain affordances that they want to target, cognisant of the trade-offs. This is important considering the observations that there appears to be many ARLEs where teacher affordance considerations are not considered at all as well as that there seem to be correlation trends which indicate trade-offs between certain categories of affordances such as between the constructive and minimalist dimensions.

8.2. Application of ARLEO as a learning analytics-based engagement observation tool for ARLEs

8.2.1. Discussion regarding the study results

Turning to the results of the experiments, a statistically significant difference in aggregate engagement, based on the underlying differences in cognitive engagement, can be observed between the experimental and control classes, in favour of the experimental class, indicating that ARLEs, at least in the early primary school context, are more engaging (particularly cognitively) than equivalent digital lessons on tablets. This finding is stable across lesson types and ARLE designs (being observed in both Nature and Society lessons as well as Mathematics) as well as having (independently coded) inverse non-engagement patterns and, overall, significantly higher non-engagement in the control class, as expected from the finding, reinforcing its validity.

A potential supporting explanation comes from student focus group interviews. In those, students indicated that usually the first 20 questions or so (i.e., 4 series of 5 questions) were interesting to them, but that afterwards they usually started losing interest. This is stable across the experimental and control class focus group representatives. However, students also describe (those of the experimental class directly based on their experiences during the school year and those in the control group recalling the ARLEs they've experienced the year before) that ARLEs are like a video game to them (note: no gamification features were implemented targeting this aspect, making it an inherent opinion), making it engaging even if the content is not so interesting any more after solving multiple sets – but it is better to continue "playing the game", i.e. being engaged with the lesson at least partially, rather than going back to your seat and waiting for the next part of the lesson. They do acknowledge the educational aspect, describing it as "learning while playing a video game", something they consider as a treat. As noted, both sets of students were exposed to ARLEs and other tablet-based digital lessons of the SCOLLAm project since the previous school year relatively often, so this feedback should not be considered as being significantly influenced by novelty factors.

A difference in behavioural engagement can be clearly observed between the Mathematics lessons and the Nature and Society lessons, in that results are inconsistent (leaning to non-significant) for the Mathematics lesson (i.e., not much difference could be observed between the experimental and control classes), while in the Nature and Society lessons students showed clear significant behavioural engagement for the ARLE through excitement expressed through running to the answer they think correct, kneeling or standing to better position themselves to scan the potential answer and similar actions. Teachers considered this a positive and showing that the experience is fun for students, especially being beneficial to students that typically have concentration problems. While this is in line with previous research [48], it could not be validated statistically.

Teachers overall consider the experience positive for both knowledge acquisition and engagement, whilst students express a preference for ARLEs, linking them positively to other "games" they enjoyed on tablets in class i.e. the sophisticated gamification experiences deployed as well as part of the SCOLLAm project [33].

Further analysis not relevant to the contributions of the thesis is available in [132], on which this section is based.

8.2.2. The special case of the second mathematics lesson

An exceptional case in the results can be found in the second mathematics lesson which does not fit the engagement patterns observed in the other lessons, in particular with regards to cognitive engagement and, based off cognitive engagement, aggregate engagement, which do not have statistically significant differences in engagement between the experimental and control classes, as well as having statistically significant behavioural engagement in favour of the control class.

Re-observing the lesson recordings, this can be tracked back to several students in the control class utilizing the environment around them to assist them in solving the mathematics problems posed. When unsure of the answers, those students would go to the multiplication table posters put up on the walls of the classroom to try to use them to help them solve the problem (focus coded as task-oriented exploration, indicating behavioural and cognitive engagement).

It must be considered in the interpretation of this phenomenon that the second mathematics lesson was the most complex lesson taken on by the students as part of the ARLE study. It showed the need for scaffolding learning, which a system not intended primarily as a research tool should provide. In absence of scaffolding, students used the available resources (multiplication tables) as well as contacting the teachers for assistance for help. The use of the multiplication tables indicates a sort of "self-augmentation" by the students, showing that simple digital lessons need more affordances.

It is interesting to note that in the experimental class multiplication tables were not consulted although available on classroom walls. Students preferred to work out the issues with help of peers (more peer interaction was observed which does not show up in results due to both peer interactions and teacher interactions being coded as emotional engagement) or teachers. This can be interpreted as the more engaging ARLE having a better effect of keeping the student more in the boundaries of the experience, without the need to search for answers outside it.

Finally, it should be noted that the results are due to several students in the control class showing this proactive and very constructive behaviour. Amongst the lower-engaged students the patterns held, with students in the control class showing sooner higher levels of non-engagement than in the experimental class (Fig. 7.12).

8.2.3. General observations by teacher and student focus groups

Providing feedback via focus group interviews, the participating teachers considered overall ARLEs as a positive and more engaging than traditional (non-digital) lessons, being, in their opinion, especially useful for review and reinforcement of previously taught lessons. They consider it a good approach to prime students with some introductory slides recapping the material before launching into the ARLE and consider that this can be used for first instruction for simpler topics, but that in general it is preferable to present the topic first through traditional teacher-led lecture, as they feel that teacher agency is needed for more complex topics for this level of maturity (early primary school) where self-regulation of learning is still developing. They especially appreciate the capability of the ARLE to enable students to answer much more training questions in the allotted time than they would in traditional in class exercises, especially with regards to math problems. Students agree with these views, considering it best that the teacher first explains and that then they "play" with the ARLE. One thing they appreciate is that their answers are private, that they are not put on the spot to answer questions publicly by the teacher but that their answer is between them and "the smart owl" (the mascot posing the question – see Fig. 7.4), where they see no shame in being told they are incorrect versus when the teacher does it, and that they can take a bit more time to figure out the answer in private if unsure.

While students claim that they always tried to make the first attempt at the answer with thought and switching to trial and error sometimes if it was not correct, the teachers had a more pessimistic opinion that many students tried via trial and error from the beginning. However, they consider that even if they are correct, the benefit of the ARLE is still there – they highlighted that in the experimental class students remembered the lessons in review a month later as shown by the fact that students could be prompted for the correct answer by making them remember the spatial layout of the models representing the answer. An example was provided about the Recycling lesson where students could be prompted to remember the reply by questions like "do you remember where the bin for this was?" as a trigger to remember to which category of recyclables an item belongs to, when reviewing the lesson contents a month after the ARLE.

A negative observed by the teachers during the Nature and Society lessons was the physical class logistics. They felt that the class could sometimes become chaotic, with students stumbling into each other in attempts to go to the desired answer. While considered OK for the occasional review session, it is considered a negative more broadly. This is mirrored by the students where, while most students considered it a fun change of pace, some found issue with the more free-form approach and lack of central authority, claiming that it was less engaging than traditional lessons. However, the teachers indicated for those students that while they claim less engagement, in their opinion observing them during the lesson (by their actions and body language), they were in fact more engaged than usual.

The teachers are worried about the lack of agency and do require more systematic feedback, as expected from design concerns and more broadly considerations arising out of STAR-ARLE [21], as the research system did not have high maturity in the awareness and control dimension. Therefore, any system deployed systematically should consider mitigation measures in these dimensions, as discussed in section 8.3.

Finally, in line with previous literature [48], teachers consider ARLEs especially beneficial for students that normally have issues with calm concentration during class. They consider three factors contributed to this: individual questions (questions being generated for each student separately), not having a list of questions at the beginning (no discouragement from seeing a long list of questions) and private answering (more freedom in exploration, no shame in answering wrong). This finding could not be statistically confirmed, however.

8.2.4. Overview discussion regarding ARLEO

Per the presented results, the ARLEO methodology allows for a systematic coding of student actions, enabling analysis of student engagement during ARLE and classic digital lesson experiences, through all three engagement categories, as needed by the relevant applicable theory frameworks. Examining the coding results, they reflect self-evident assumptions regarding student engagement: students start highly engaged (although at different levels depending on the category), with drop-off(s) as the lesson progresses. With the lesson design being such that the student may take on more series of questions based on their own self-initiative, it is fully expected that student engagement will drop-off over time and that non-engagement actions will increase, which is indeed what occurs. Therefore, ARLEO shows to be in line with expectations of patterns of student engagement, increasing its validity.

By shifting to video recording and dynamic catalogue construction through the constant comparative method, ARLEO gains a lot of flexibility compared to previous observation instruments, allowing for adjustments to the catalogue to cover actions specific to the learning experience, whatever those may be, as well as allowing for more comprehensive coding, allowing for coverage of more categories of engagement than previous observation instruments. This is important in new fields such as ARLEs as they require precisely catalogue flexibility in combination with overall comprehensive coverage of types of engagement to assist in their benefits analysis in terms of engagement.

The observer-coders also note the need for two viewpoints with an estimate that with two properly positioned (overlapping orthogonally) viewpoints only up to 10% of actions are difficult to encode, while for a single-viewpoint (single-camera) recording the estimate is 20% - 50%, depending on the angle and the lesson design. Clearly, additional camera viewpoints would allow for a further reduction of difficult to code actions, but it is considered that they would represent severely diminishing returns in terms of needed setup time for the recording, equipment handling time as well as complexity of the work for the observer-coders.

8.3. Assessing the implementation, via SCOLLAm AR tools, of the model

8.3.1. Comparing the SCOLLAm AR tools with the model

When compared against the system model presented in 6.1, it can be observed that two optional components were not developed for the implemented model, thus limiting its affordance maturity in the awareness and empowerment dimensions.

Those include the teacher-oriented components of Experience execution teacher live interface and Classroom-scale live display. Their development, as well as integration of developments discussed below, was not possible due to limited resources and time pressure during the study period in 2017 with regards to the ARLE capabilities.

As discussed in section 8.2.3, having limited teacher awareness facilities, where only post-lesson feedback on student activity is available, as was the case with the SCOLLAm platform during the study period, does produce negative effects on teacher orchestration load and should therefore be mitigated. A classroom-scale live display was developed for the platform in the context of gamification capabilities and is thus discussed in the potential improvements section below.

In terms of the maturity of the rest of the components versus model requirements, the ARLE modules component can be observed to be limited to questions and answers in terms of constructiveness and does not have technological capabilities for cooperation in the version utilized during the 2017 study period, but otherwise complies with the affordances requirements that are not dependent on teacher-oriented real-time capabilities being present.

The Author lesson designer is fully compliant with the affordance requirements; with the caveat that its cooperation capabilities were not utilized during the 2017 study period. The InForm viewer is fully compliant with the affordances requirements as are the platform / server components (database and web services).

8.3.2. STAR-ARLE scorecard for SCOLLAm AR tools

With those considerations in mind, a self-evaluation can be performed of the implemented system with the STAR-ARLE rubric, to be aware of the maturity trade-offs of the implementation decisions, as discussed in section 8.1.2. Offered affordances by the SCOLLAm platform (as of the 2017 studies), are to be compared against the detailed rubric dimension definitions and matched against the most closely matching in description level on the scale. Comments are provided to assist in clarifying positioning against each techno-pedagogical affordance dimension. The thus generated scorecard table is presented in Table 8.1.

Examining the results, it should be observed that the implementation follows the techno-pedagogical maturity in most ARLEs per [21] for student-oriented affordances, with a higher score than average for the intentional dimension. In terms of teacher-oriented affordances, it is above-average in all categories, showing the benefits of a system supporting ARLEs rather than having a stand-alone application. Potential improvements to reach the highest affordance levels are discussed in the following section.

TABLE 8.1
STAR-ARLE SCORECARD FOR THE SCOLLAM MODEL IMPLEMENTATION

(Category ID) Dimension	Score	Comments
(ML1) Constructive	2	The SCOLLAm system contains facilities for question-and-answer functionalities surfaced via the ARLE modules or other widgets, but it does not have any techno-pedagogical affordances for divergent knowledge construction through synthesis or reflection in the 2017 study configuration.
(ML2) Authentic	2	The problems presented via SCOLLAm implemented ARLE modules are real-world and relevant to the curriculum, but experience design is not such to encourage investigation or expression.
(ML3) Intentional	2	SCOLLAm ARLE modules clearly indicate to the student when they have made a mistake but there is no scaffolding to assist in knowledge gap filling.
(ML4) Cooperative	1	SCOLLAm ARLE modules were not developed with experience design nor other techno-pedagogical affordances for cooperative work. While it has been observed in practice, it is an emergent phenomenon.
(OL1) Integration	3	Through the integration with the rest of the SCOLLAm platform and lesson design capabilities of Author, it is possible to create fully integrated lessons with ARLE experiences being a well-integrated component.
(OL2) Empowerment	2	The teacher can disable the experience via the Author interface, but this global affordance is the extent of the capability to control the flow of the experience; it is not possible to act individually or specifically.
(OL3) Awareness	2	As deployed during the 2017 studies, the SCOLLAm ARLEs did not contain facilities for teacher real-time view of student progress, but only post-experience reports could be provided.
(OL4) Flexibility	3	It is possible to adjust the experience in detail with the Author lesson designer – as can be seen in 7.2, completely different lessons were covered by the utilization of the same ARLE module with different parametrization. Interventions can be made via Author while the lesson is ongoing, but this should, of course, be done with care as changes are global.
(OL5) Minimalism	3	All interfaces (Author, InForm and ARLE modules) are designed with minimalism principles in mind and contain only the necessary information, as can be seen in Fig. 7.4.

8.3.3. Potential improvements

Before examining specific improvements, it should be recognised that in the development of the ARLE capabilities of the SCOLLAm platform, focus was placed on integration of those capabilities into the wider platform in order to raise teacher-related affordances, noted as sorely lacking in maturity in [21], which was generally achieved, showing value in the approach of embedding ARLEs into a wider LMS. As well, developments of the platform to support other avenues of research were going on in parallel; some of those could not be integrated with the ARLE work at the time, but they signpost easy potential improvements to raise the maturity levels where they are lacking.

As noted, student-oriented capabilities were generally aligned with the maturity level of other ARLEs, indicating what is typically achievable with generally available effort levels.

In terms of *constructive* affordances, attaining level 3 is mainly a question of lesson design and consequent ARLE (module) design. The SCOLLAm project was focused on in-classroom experiences and there were finally no field experiences attempted, due to safety concerns over the distraction of using tablets outside in an urban environment with early primary school students. Consequently, lesson designs incorporating investigative or own experience aspects that are typically seen in ARLEs, such as location-based investigations (see section 3.5) could not be developed. In terms of infrastructure, there is nothing preventing the development of an ARLE module that could be incorporated in lessons where there would be more student investigation, synthesis, and reflection. Similar considerations apply to the *authentic* dimension.

In terms of the *intentional* dimension, there is a clear need for scaffolding affordances to be implemented to assist students in having support to construct a second attempt at answers. A scaffolding approach for the Mathematics ARLE (AR.Math ARLE module) was developed towards the end of 2016, supporting 1st grade addition and subtraction lessons, which can serve as example of such a functionality. The scaffolding is based on observed actions of students counting pens to help them with conceptualizing addition. Thus, a special support paper marker (indicated with a happy question mark) which can be used to indicate a need for scaffolding was introduced, which allows an overlay of virtual pens to be displayed to help the student count the needed sum (Fig. 8.1). As the studies in 2017 were in the 2nd grade and this scaffolding approach was not appropriate for use there (with mathematics operations being used including addition, subtraction, multiplication, and division up to 100), the scaffolding functionality was not retained.

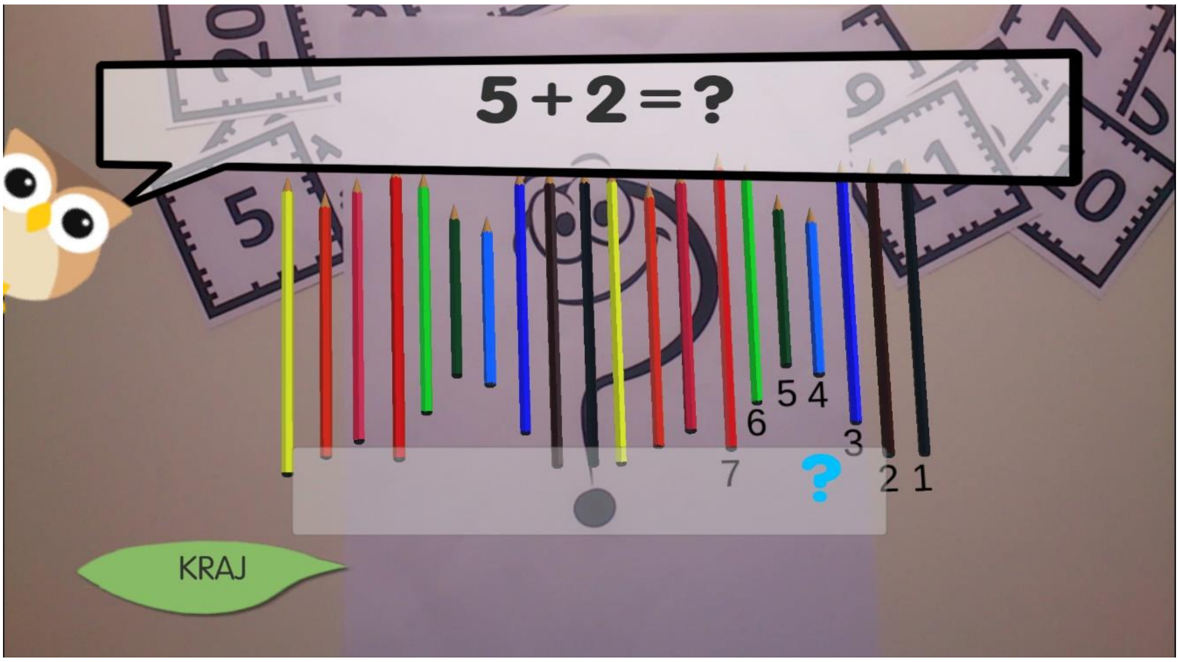

Fig. 8.1. Scaffolding capability implemented in the AR.Math ARLE module for Mathematics problems solving, which assists 1st grade students in improving their knowledge of basic sums. Adapted from [148].

In terms of the *cooperation* dimension, there were no developments of ARLEs with those affordances. However, as part of the wider SCOLLAm research efforts, significant efforts were deployed to create cooperation and collaboration affordances [31]. A further development would therefore be to utilize those capabilities and their interfaces to design a lesson and supporting ARLE module which utilizes those capabilities to lean mathematics or other appropriate contents. This approach, of there being platform developments which could be utilized to increase affordance maturity relatively easily, highlights the benefit of building ARLE capability into a broader LMS platform.

In terms of teacher-oriented affordances, the capabilities described in SCOLLAm ARLE platform already represent the potential for top level affordances in *integration, flexibility,* and *minimalism* domains.

Lacking capabilities can be identified therefore in the *empowerment* and *awareness* domains. To improve the maturity of the affordances in the *empowerment* domain, it would be necessary to develop a teacher live interface which would allow for oversight and intervention by the teacher as needed. Such a component is not available in the SCOLLAm platform, but has been observed in an ARLE before [121].

With regards to the *awareness* domain, the level of affordances could be improved through implementation of the aforementioned teacher live interface as seen in [121], or through other components that give an easy overview of student progress, such as classroom-scale live displays. While not employed for ARLE research, such functionality was implemented in

SCOLLAm to support gamification research work [33] and thus has relatively easy potential to be integrated (Fig. 8.2).

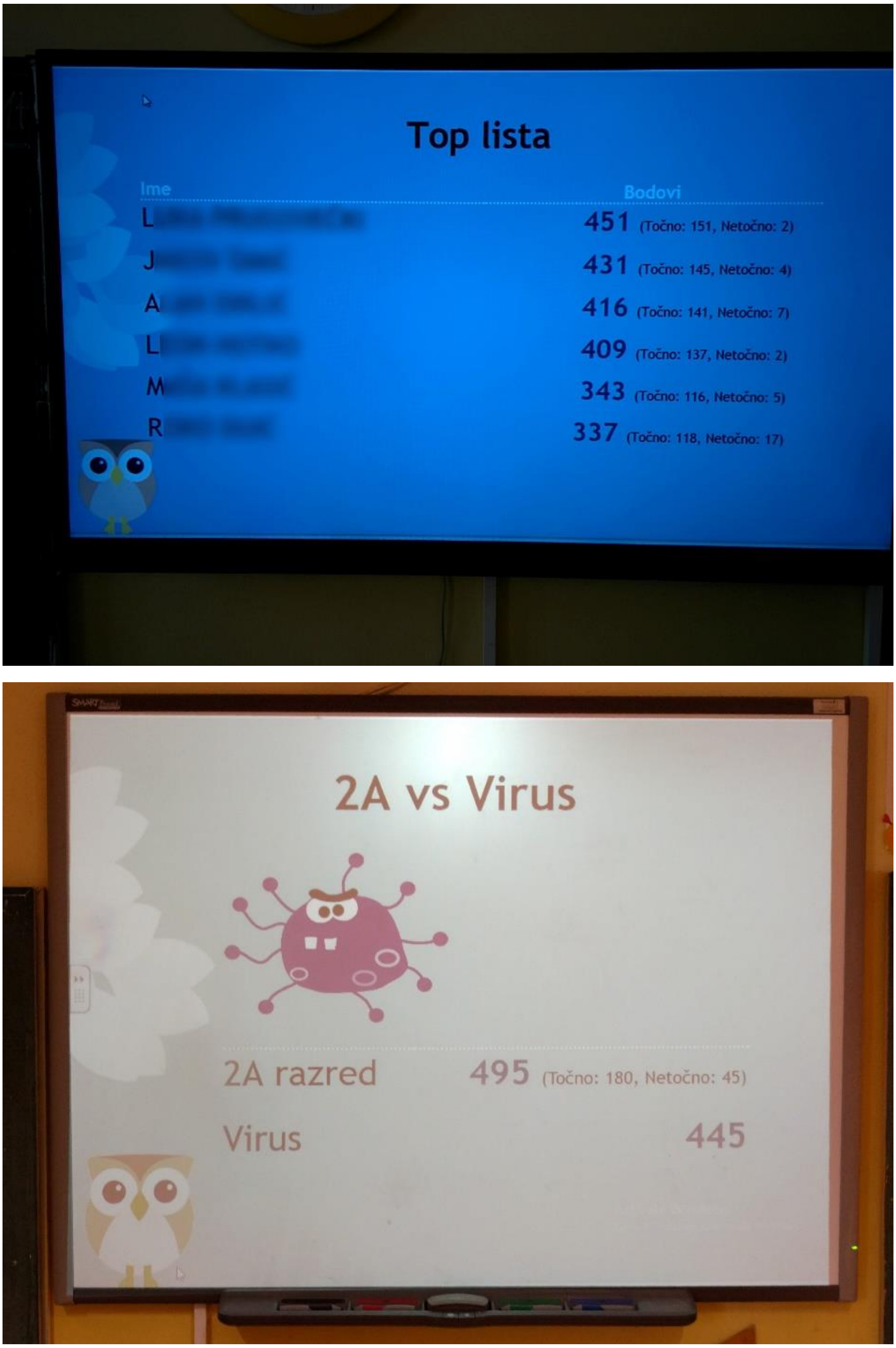

Fig. 8.2. Leader board (top) and class-wide status (bottom) displays showing in real-time student efforts as part of SCOLLm gamification research, serving as potential examples for integration to improve ARLE awareness affordances. Adapted from [33].

8.4. Limitations

8.4.1. Limitations of the performed study

The findings in this thesis are limited by the nature of the research project it was a part of, namely a pilot project intended to start the exploration of the domain in Croatia, limited to partnership with one primary school. Thus, the results cannot be fully controlled for in terms of contextual systematic biases, as well as limiting the findings to the early primary school context. The studies were held in the second grades of the participating primary school, with limited class sizes. This was mitigated, as explored in the results, through statistical tests to ensure relevancy, but that only mitigates distribution and data quality issues; it does not mitigate for the specifics of the environment such as the partner school being an urban, working-class neighbourhood school teaching according to the Croatian curriculum. It is not possible to evaluate if there would be an impact, for example, from conducting the same experiments in a school which systematically deploys tablets or laptops all the time to students or where student backgrounds or the curriculum (including teaching methods and lesson contents) are different.

Due to limited resources, it was not possible in time to develop a model implementation that fully provides all affordances envisioned by the theoretical model.

Like with any observational instrument, ARLEO codes for observed actions and not for actual thought or considerations of the subject. Therefore, while their observed actions can be coded for perceived engagement, whether a student is engaged in their mind, particularly cognitively or emotionally, is not possible to be certain of.

8.4.2. Limitations of the STAR-ARLE review

In terms of limitations of the findings of the STAR-ARLE review, it must be noted that the review was conducted on a corpus as constructed based on the methodology described in section 3.4, having the potential to leave out relevant papers due to simply missing them due to the chosen methodology. That is mitigated with the use of multiple previous reviews and a dual search (IEEE/WoS) strategy to, firstly, identify key known ARLEs and, secondly, ensure a wide scope for the search. Therefore, it is unlikely that significant relevant articles were missed, unless due to them not fulfilling the criteria to apply the rubric to them (there are many articles that are not sufficiently comprehensive with regards to the presentation of the ARLE at issue in both the technological and pedagogical aspects in the same article). Similarly, while there is potential for ARLEs to be miscategorised due to their presentation articles not correctly showing their affordances, the high bar set by the inclusion criteria is likely to filter out such articles as they require comprehensive descriptions of ARLEs.

Many articles were identified which do not describe the role of the teacher in the ARLE execution although they are occurring in a classroom environment, which were therefore not selected for the corpus. This can potentially be linked to the previously described issue of ARLE designers not considering teacher affordances at all – it being something outside of their scope of concern. Thus, it is possible that there are more ARLEs than reported with low teacher-related affordances. As the overall conclusion is that in those regards the field is not very mature, any such missing articles could not change the conclusions fundamentally.

As well, it must be noted that STAR-ARLE is, by its nature, inherently subjective, as it requires judgement in identifying techno-pedagogical affordance patterns to classify an ARLE within the dimensions. This was mitigated with the use of the inter-rater reliability check, per best academic practice.

Finally, it must be noted that the review was conducted based on a corpus developed in 2016 as part of the publication of [21], which raises the question if the conclusions are still valid today. With regards to this, it must be noted that the review encompassed ARLEs from a much longer period (early 2000s to 2016) and that there have not been fundamental changes in the field since then; nothing like the initial breakthrough due to the deployment of smartphones and tablets. Observing the field, main changes can be observed in the popularity of AR in general, but which is in general not replicated in educational environments, as well as additional refinement of technology; there have, however, been no meaningful changes in the basis of the technology that is in wide usage (smartphones and tablets), especially when considering the context of early primary school education. As for the purposes of this thesis only broad trend findings are used to ground the model development in the needs of the field as well as STAR-ARLE itself being a contribution (albeit a high-level one which is not dependent on current technological particulars), this concern can be considered a limited, acceptable, and mitigated risk.

8.4.3. ARLEO coding cost limitations

The flexibility of ARLEO does come with a cost – ARLEO depends on the quality of its observer-coders in comprehensively encoding student actions (a time-intensive task) as well as understanding engagement well to properly do axial coding i.e., assigning engagement categories to focused codes. The workload for initial coding is intensive – it requires observation of each student during each the entirety of each lesson plus the time needed to encode observed student actions. This time can be described with the following Formula 8.1.

$$t_{cl} = n_s \cdot t_{lo} \cdot cf$$

t_{cl} - time needed to initially code an observed lesson
n_s - the number of students for which initial coding needs to be performed
t_{lo} - the length of time of the observation of the lesson that is being examined
cf - the correction factor to account for the time the observer-coder needs to encode the observed actions (dependent on the skill and efficiency of the observer-coder)

Formula 8.1. Time needed to initially code an observed lesson

For example, taking the Recycling lesson as example, this comes out to:

n_s = 18 students in class 2A + 15 students in class 2B = 33 students total

t_{lo} = 10 minutes (the same for both the experimental class and control class)

cf = assumed at 1,5 (50% more time is needed to encode a lesson for one student than its runtime)

$t_{cl} = 33 \cdot 10 \text{ min} \cdot 1{,}5 = 495 \text{ min} = 8{,}25 \text{ h}$

to encode a 10-minute observation of the Recycling lesson held in the experimental and control classes.

Such exhaustive coding is necessary as otherwise numerous student actions are missed. The estimate of the participating observer-coders is that only 20% of student actions are captured through a *one-time viewing* approach, where the observer-coder observes the recording from beginning to end trying to encode all actions they see, without specific focus on a particular student. The similar (poor) results are found with live (in-person) real-time observation.

The lack of a fixed catalogue does present a negative as it means that there is a lack of a reference database of results, making it impossible to categorise a student's engagement in absolute terms to assist with the determination if the student is overall highly, normally, or not engaged. This does not detract from its use as a research instrument for allowing comparative analysis in experimental studies or over multiple DBR cycles, but it makes it unsuitable as a tool for teachers to evaluate the engagement of individual students. At best, it allows tracking of specific student's engagement patterns over time (i.e., if their engagement is increasing or decreasing) if diligently applied over multiple lessons.

Overall, significant time investment by knowledgeable observer-coders is necessary to successfully apply the ARLEO algorithm, but it does give a flexible, comprehensive encoding of student engagement during observed lessons, suitable for comparative statistical data science analysis, in line with learning analytics, while considering the necessary theory basis and design affordances of ARLEs, unlike preceding observational instruments. This analysis is further developed in the author and contributors' work [134].

8.5. Potential future work

8.5.1. Applicability of ARLEO to individual student monitoring

Although not explored in the work of the author further, ARLEO could also be used for comparing amongst students or the engagement patterns of one student compared to average engagement patterns for the class, applying the various other learning analytics techniques on a rich dataset. Thus, it could be used to identify students at risk, keeping in mind that derived (comparative) indicators are considered more sound in learning analytics [97]. As well, ARLEO could be used for longitudinal engagement analysis of specific students or classes, examining the levels of engagement of students over multiple lessons over a period of time.

The limitation of such approaches is that without a fixed catalogue it is impossible to have baseline metrics, thus making any kind of analysis against fixed thresholds artificial and unsupported, requiring a comparative approach against class averages or prior engagement levels of the same student/class.

8.5.2. Automating ARLEO

The expensiveness of ARLEO coding is a noted limitation of the presented instrument. The natural question is therefore is there is a way to optimize the coding process by augmenting or even fully replacing the observer-coder with automation.

D'Mello's work in this area should be instructive [84]. D'Mello proposes a model where AI based computer vision algorithms would be able to identify and classify actions observed, which could be a future development, replacing the need for an observer-coder, however this requires both further advancements in the underlying theory and practice (to which this thesis contributes to) as well as further development of computer vision algorithms as well as their experimental application to the purposes explored in this thesis.

If this should come to pass, a more optimized approach to ARLEO, where an initial student action coding pass is done by the automated AI expert system could be imagined, with further steps (focused and axial coding) being done by an expert observer-coder. It being understood that period coding can and has already been automated. In the most positive imagined case, the full ARLEO coding could be done in an automated fashion.

8.5.3. Applicability of ARLEO to activity log processing

Logging of student activity and analysis thereof represents one of the pillars to learning analytics when applied to student performance during a lesson and even for analysis of student performance during a semester (analytics of student interactions with CMSs and similar systems) [40], [149]–[151].

This is possible because in systems where the context of activity is purely virtual, it is assumed that user action is also expressed fully through interaction with the virtual artefacts (aside from edge cases such as analysis of user experience for students with disability and similar activity where the focus is on precisely the man-machine interface).

With the mixed reality situation in Augmented Reality, this is no longer the case – many if not most relevant student actions are not expressed in a way that can be easily captured by traditional (virtual) logging systems, which is a problem as learning analytics research shows that the number of significant features and their categories is key to successful use of learning analytics [152].

This was experienced by the SCOLLAm researchers when researching this topic, where, instrumented for traditional data collection (taps of actions by students), the logging contents were ultimately found unusable, as it was not possible to determine the context of the action (for example, is a wrong answer a deliberate attempt at an answer or a student trying out to scan an object with the tablet without any deliberate intention to respond to the question). As well, due to the design-based research approach, logging functionality was not consistently available with consistent structure, making any comparative analysis unfeasible.

While further research in this direction was not possible within the SCOLLAm context, the lessons learned could be applied to the ARLEO algorithm to enhance the various engagement determinations if the ARLE used was properly instrumented.

If the intent would be to improve cognitive engagement determination, an addition to the video analysis could be an analysis of student activity on the device, i.e., determining if during a period the student is either looking at preparatory materials (that is, investing into understanding of the mastery of the subject) or attempting to answer questions, which could be helpful to determine if a particular initial code belongs to a focused code and/or if a focused code should be categorized as cognitive engagement. Care must be taken that some non-engagement actions such as randomly trying out answers are not mischaracterised here; further research, which would include both log analysis and analysis of video at the same time of occurrence, would be needed to determine patterns for a specific ARLE which would allow the distinguishing of such positive and negative engagement. Work done by Worsley [106] would be instructive in such analysis.

For behavioural engagement, logging of device sensors (such as the gyroscope, compass and accelerometer) could be used to determine if the student was engaging with the content in a physically active way. This would again require that instances of behavioural engagement are identified via ARLEO video-analysis, and then the patterns in the logging analysed to determine what kind of sensor results engaged actions provide. An analytical fusion, requiring subjective boundary-setting, between the observed behaviour on video and logging information, would again be required, necessitating the involvement of an observer-coder.

Emotional engagement is in principle not possible to be captured via logging as it involves interaction with classmates and authority figures. Should the ARLE contain a digital collaboration component (i.e. that students need to collaborate between themselves or with the teacher utilizing digital artefacts available on the device), a partial analysis using logs would be available [84], but it would still not capture events such as real world classmate discussions, requesting real world assistance form an authority figure and similar, which comprise the majority of emotional engagement events.

Finally, applied to non-engagement actions, logging is not helpful in positive identification of such actions in most cases as they occur in the real-world context (abandoning the tablet to play, disengaged boredom etc.) and are not visible at the virtual logging level. However, correlation of activity logging with video recording could help to distinguish between engagement and non-engagement in situations where the student escapes into the virtual world. For example, when a student is working intently on a tablet, it is difficult to determine from videorecording if they are cognitively engaged and looking at the virtual materials of the lesson in order to better understand the material or if they have gone to another application (i.e. are abandoning the lesson and are therefore non-engaged) or are bored and just randomly tapping on the tablet (again an activity that should be classified as non-engagement).

The considerations expressed in this section are built upon field observations during SCOLLAm experiments and data analysis and require further research with appropriately instrumented ARLEs.

9. CONCLUSION

The presented thesis contributes to the state of the art in the Technology Enhanced Learning domain through contribution to the understanding of ARLEs – learning experiences utilizing augmented reality.

Based on developments and experiments conducted during the SCOLLAm project, a pioneering project exploring mobile learning with tablets in Croatian primary schools, and thus focusing the findings to the early primary school context, the work presented finds that ARLEs have positive effects on student engagement, in particular cognitive engagement, with student engagement being noted as a predictor of future academic achievement.

This is determined to be, aside from their inherent affordances, due to students perceiving ARLE use as play, while acknowledging the educational aspects of it. Through discussion with teachers, and validated by student opinion, ARLE use in early primary education is best positioned for review and repetition of materials in a topic, after a first pass presentation led by the teacher. Alternatively, they can be used for first presentation of simple topics.

The above findings are based on experiments conducted in 2017 utilizing the SCOLLAm system, as an instantiation of the model for learning support systems for utilizing ARLEs in early primary education, presented in this thesis. Due to the use of said platform, with its affordances developed based on findings regarding the techno-pedagogical maturity of the field and the gaps thereof, it was possible to isolate AR use as the experimental variable, with an experimental class experiencing ARLEs and a control class experiencing the same content in the format of a traditional digital lesson. With AR as the experimental variable thus isolated, the experiments and consequent data analysis have allowed for findings based on solidly grounded experimental work, thus far lacking in the field.

As the overall SCOLLAm tooling was proven to have positive student benefits overall in other domains of research, therefore confirming positive effects in the ARLE domain serves as adding ARLEs to that overall comprehensive model validation.

In order to perform the aforementioned data analysis, it was necessary to develop the *Augmented Reality Lessons Engagement Observation* instrument, or ARLEO for short, an instrument, including coding algorithm, based on learning analytics principles, which allows for coding of student actions during ARLEs through the use of a dynamically generated coding catalogue through constant comparative method coding approaches, allowing for the coding of student actions in a dynamic environment such as during the use of ARLEs, which surfaces actions not typically found in the classroom. Using videorecording as the observational data gathering method, ARLEO allows for comprehensive periodic coding, creating a discretized view of engagement of each student in 15s intervals for each engagement category, thus developing a rich data set as needed to be able to perform data science-like analysis of the data, in line with learning analytics approaches. All the engagement categories found in the used engagement classification are supported – cognitive, emotional, and behavioural, as well as aggregate (any of the aforementioned categories) and non-engagement through linking initial student action codes via focused codes to engagement categories. The flexibility that affords the comprehensive coding has as a downside the necessity of significant time investment by knowledgeable observer-coders to perform the initial student action coding.

The presented model for support system for learning with augmented reality in early primary school education posits the need for a distributed architecture, with a core developed along learning management system (LMS) principles, and with ARLE modules being one interface to access generic content data, in line with findings regarding affordances for students and teachers in ARLEs, where the maturity of affordances oriented towards teachers was found to be lacking, necessitating their improvement via integration with an LMS-like platform.

Those findings were determined through a comprehensive literature review of ARLEs done with the developed *Student and Teacher-relevant considerations' Assessment Rubric for Augmented Reality Learning Experiences* (STAR-ARLE), which allows for a high level techno-pedagogical maturity examination of ARLEs by combining examination of student-related affordances considerations via the *Meaningful learning with ICT* framework with the examination of teacher-related affordances considerations via the *Orchestration load reduction* framework. Reviewing the level of maturity of the field, it was noticed that while ARLEs tend to have a decent level of affordances for making student learning meaningful, they tend to have poor affordances to help teachers with orchestration load, making ARLEs more difficult to use as part of well-running and well-orchestrated lessons. This necessitated the contribution of developing an exemplar model on how this could be ameliorated, while considering the affordances considerations in terms of every component.

It is the hope of the author that other research efforts will use this work as a steppingstone and source of useful instruments such as STAR-ARLE and ARLEO for broadening the affordances findings regarding ARLEs through more experimental work that clearly isolates AR as the experimental variable, in broader contexts in terms of student maturity and level, as well as deepening the findings in the early primary school domain.

It is as well hoped that the developed instruments can be used by ARLE designers in general to assist them in their ARLE development by enabling them to consciously choose through STAR-ARLE self-examination desired affordances levels for their ARLEs, with their attendant trade-offs, while being able to utilize ARLEO as a flexible observational methodology to support their developments through iterative design-based research in cooperative work with teachers, which is envisioned in the literature as the best development approach for ARLEs.

Thus, taking all the above analysis and conclusions into account, this thesis contributes to the current state of the art of AR in education, as a subfield of interest in Technology Enhanced Learning, itself a cross-disciplinary field between computing and pedagogy, by:

1) Determining specific metrics – the STAR-ARLE rubric – for techno-pedagogical maturity of learning with augmented reality based on integration and adaptation of existing frameworks which consider the requirements of students and teachers during lesson execution. When applied in literature review, it is shown that the field of ARLEs is currently lacking techno-pedagogical maturity, having some maturity in student-related considerations, but lacking maturity when it comes to the concerns of teachers, as expressed via orchestration load-relevant affordances. Additionally, the review reveals a lack of relevant experimental work in the field, which isolates AR as the variable being observed, which is contributed to with the study summarized in point 3, which addresses that gap in so far as engagement during ARLEs in early primary education is concerned.
2) Algorithms based on learning analytics with application in video records processing in learning with augmented reality in early primary education are developed and presented in this thesis as part of the ARLEO engagement observational instrument, showing that ARLE effects on engagement of students can be comprehensively analysed by applying relevant engagement theory, observational approaches for coding of student actions and learning analytics approaches to large dataset data analysis. Applicability of ARLEO to activity logs processing is discussed in detail in the discussion section.
3) Based on considerations developed in STAR-ARLE and the consequent review via STAR-ARLE, a model of a system for supporting learning with augmented reality based on the proposed algorithms (in terms of enabling the result analysis via ARLEO) is presented in this thesis. The study conducted via SCOLLAm AR tools (AR.Curious and AR.Math), as an instantiation of said model, led to identification of advantages and disadvantages of digital lessons for tablet computers that use augmented reality in early primary education. Namely, utilizing ARLEO to code and analyse student engagement in experiments conducted in the second grade of the participating primary school, it is possible to determine, while being cognisant of stated limitations and special cases discussed, that students are more engaged with ARLEs, especially in terms of cognitive

engagement and lessened non-engagement, with disengagement occurring later in the ARLE experimental class than in the control class. Taking into account engagement theory, which posits that higher engagement is an indicator for higher academic achievement and lower drop-out rates, this indicates that ARLEs present an advantageous tool for early primary education. Per reflection of student and teacher focus groups, they are best deployed for purposes of repetition and reinforcement of lessons presented.

10. ETHICS COMPLIANCE STATEMENT

Due to the subjects being early primary school students, ethical research guidelines had to be respected. Therefore, before commencement of any in-class or otherwise student-involving activities, an agreement was concluded between the University of Zagreb Faculty of Electrical Engineering and Computing and the partner Primary School Trnjanska, laying out the roles and responsibilities of all stakeholders, including principles of consent by students, their parents or guardians and that the activities would always be done in the presence of the class teacher, who was always entitled to intervene and stop the activities if they considered them inappropriate in any way. Consent forms were signed by all participating students' parents or guardians, the students were clearly informed of the activity to take place and given an opportunity to not participate. As part of the consent, permission was given to collect lesson observations via video recordings, software logs and field observations, focus group interview recordings, as well as collection of background information on students from teachers.

The SCOLLAm project was reviewed for ethics compliance and found compliant by the Ethics Committee of the University of Zagreb Faculty of Electrical Engineering and Computing.

Due to the above, the data that support the findings of this thesis are available on request from the author. The data are not publicly available due to privacy and ethical restrictions.

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12. APPENDICES

A – Template for ARLEO coding

The template for ARLEO coding is presented in this appendix in detail. To be used with the periodic coding algorithm for which the code is presented in appendix B, it is necessary to follow the template exactly in Excel, with the correct naming of all sheets and columns and correct data type entry.

The template consists of three sheets:

Data – sheet containing the initial codes of student actions.

Focused Actions – sheet containing the encoded focused codes and their mapping to initial codes.

Focused Actions Engagement – sheet containing the axial coding i.e., assignment of focused codes to engagement categories.

The **Data** sheet should be set up as instructed on the following page (note: text direction adjusted for space and presentation reasons; example data used), with columns *Corr. begin., Corr. end, Focused Event, Engagement – Behavioural, Engagement – Emotional, Engagement – Cognitive* and *Non-engagement* being autogenerated with the following formulas:

Corr. begin.	*=[@Beginning]-[@Correction]*
Corr. end	*=[@End]-[@Correction]*
Focused Event	*=VLOOKUP([@Event],<FA table>,2,FALSE)*
Engagement – Behavioural	*=VLOOKUP([@[Focused Event]],<FAE table>,2, FALSE)*
Engagement – Emotional	*=VLOOKUP([@[Focused Event]],<FAE table>,3, FALSE)*
Engagement – Cognitive	*=VLOOKUP([@[Focused Event]],<FAE table>,4, FALSE)*
Non-engagement	*=VLOOKUP([@[Focused Event]],<FAE table>,5, FALSE)*

with

<FA table> meaning the table in the **Focused Actions** sheet.

<FAE table> meaning the table in the **Focused Actions Engagement** sheet.

Date	Lesson	AR Module	Category	Class	Student	Camera	Correction	Beginning	End	Corr. begin.	Corr. end	Event	Focused Event	Engagement - Behavioural	Engagement - Emotional	Engagement - Cognitive	Non-engagement
01/01/2021	Example	AR.Example	Experimental	Exp. Class	EC001	Right	01:00	05:00	06:00	4:00	5:00	Reading carefully	Task-oriented work	0	0	1	0
10/05/2017	Example	AR.Example	Experimental	Exp. Class	EC002	Right	01:00	03:20	03:35	02:20	02:35	Happy	Task-based happiness	1	0	0	0
10/05/2017	Example	AR.Example	Experimental	Exp. Class	EC003	Right	01:00	03:20	03:50	02:20	02:50	Solving	Task-oriented work	0	0	1	0
…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…

The **Focused Actions** sheet should be set up as instructed per example below:

Action	**Focused Action**
Reading carefully	Task-oriented work
Happy	Task-based happiness
Solving	Task-oriented work
…	…

The **Focused Actions Engagement** sheet should be set up as instructed per example below:

Focused Action	**Engagement - Behavioural**	**Engagement - Emotional**	**Engagement - Cognitive**	**Non-engagement**
Task-oriented work	0	0	1	0
Task-based happiness	1	0	0	0
…	…	…	…	…

An empty template is available in the repository indicated in appendix D.

B – ARLEO periodic coding generator

The ARLEO periodic coding generator code written in C# allows for the generation of period coding based on a properly filled-in ARLEO template presented in appendix A.

Input parameters (mandatory command line arguments)**:**

***<path to data>* -** filesystem path to the excel table formatted in line with the template in appendix A containing focused coding data.

***<export path>* -** filesystem path (including filename) for the output file containing periodic coding.

***<period>* -** the length of the period to use, in seconds. Per the ARLEO observational instrument process flow and algorithm in section 5.2, by default this should be 15s. Must be entered as a positive integer number.

Note: requires the EPPlus library (available via NuGet at https://www.nuget.org/packages/epplus/4.5.1) for manipulating Excel files. Developed with EPPlus version 4.5.1.

The full code is available in the repository indicated in appendix D.

C – Final SCOLLAm AR tools

The final version of the SCOLLAm AR tools is available in the repository indicated in appendix D. Included are the final .apk (Android package) file, as well as a user and technical manual, prepared by SCOLLAm AR contributors[5].

D – Repository of appendices

The reposiory of the appendices is available on:

https://www.dropbox.com/sh/beajjvlw0ut81yw/AABfL6hDHNpXiRB6GjQnoe1Ga?dl=0

Access password: ARLEO

[5] Note on authorship: The author, as the research coordinator for the AR domain, supervised, assisted, and contributed to the development of AR Widgets and Applications and associated control HTML5 Widgets done by Master-level students Mirna Domančić [153], Manuela Kajkara [148], and Petra Vujević [154], as documented in their theses. The final code and guides presented in the repository represent a joint effort, where the presented manuals were prepared based on materials by the Master-level students and revised by the author and the SCOLLAm principal investigator, Ivica Botički. The code and manuals represent the final state of the AR tools at the end of the SCOLLAm project.

13. BIOGRAPHY

Neven Drljević is a European official, holding the post of Head of the Software and Cloud Assets Management Service at the European Parliament (EP). Born in Zagreb in 1985, he has earned his BSc and MSc in Computing degree from the University of Zagreb Faculty of Electrical Engineering and Computing (FER), in 2011 and 2013, respectively, where he specialized in Software Engineering, Project Management and Technology Enhanced Learning (TEL).

In his professional work, following freelance engagements during Bachelor and Master studies, he was employed as a Teaching Assistant at the Zagreb University of Applied Sciences (TVZ) during the 2013/2014 academic year, followed by the appointment at the European Parliament in July 2014, as Project Leader for developing the Software Asset Management capabilities of the Parliament, within the Directorate-General for Innovation and Technological Support (DG ITEC). In June 2018, he was delegated to coordinate the Individual Equipment Management service. In February 2020, he was promoted to Head of Service of the newly created Software and Cloud Assets Management service. He is also the Data Protection Correspondent for his Directorate within DG ITEC.

In parallel to his professional work, since 2013 he has been engaged in part-time PhD studies in Computing at FER, focusing on Augmented Reality Learning Experiences as an aspect of TEL. In that context, he was the coordinating researcher for the AR domain for the SCOLLAm project (2014-2017).

From 2012 to 2014 he held the office of Member of the Youth Advisory Board of the City of Zagreb. From 2013 to 2014 he was elected as Postgraduate Student Representative in the Faculty Council of FER.

He was recognised with the Special Rector's Award of the University of Zagreb in 2012, the Ericsson Nikola Tesla Award (3rd place) in 2012, the Best Student Computer Program of FER (2nd place) Award in 2012, the Best Student Paper Award at MIPRO 2013 and most recently with the "Certificate of gratitude and appreciation (preparations for the 9th legislative term)" of EP DG ITEC in 2019.

14. PUBLISHED WORKS

14.1. Journal articles

1. Drljević, N., Botički, I., Wong, L., 'Investigating the different facets of student engagement during augmented reality use in primary school', British Journal of Educational Technology, February 2022.
2. Drljevic, N., Wong, L. H., Boticki, I., "Where Does My Augmented Reality Learning Experience (ARLE) Belong? A Student and Teacher Perspective to Positioning ARLEs", IEEE Transactions on Learning Technologies, Vol. 10, No. 4, October 2017, pp. 419–435.
3. Boticki, I., Barisic, A., Martin, S., Drljevic, N., "Teaching and learning computer science sorting algorithms with mobile devices: A case study," Computer Applications in Engineering Education, Vol. 21, No. S1, March 2013, pp. E41–E50.

14.2. Works in conference proceedings

1. Drljević, N., Domančić, M., Botički, I., Kajkara, M., "Designing Extensible and Flexible Augmented Mobile Learning Digital Lessons," Proceedings of the International Conference of the Learning Sciences (ICLS), Singapore, 2016, pp. 1193–1194.
2. Kajkara, M., Drljević, N., Botički, I., "Kako povezati virtualni i stvarni svijet: izvještaj o primjeni proširene stvarnosti u osnovnoškolskom obrazovanju," Proceedings of the Carnet User Conference 2016 (CUC2016), Rovinj, Croatia, 2016.
3. Čarapina, M., Jagušt, T., Drljević, N., Botički, I., "A story of SCOLLAm: mobile and collaborative learning on tablet computers in one primary school in Croatia," Proceedings of the First Association of Visual Pedagogies Conference (AVPC 2016), Zagreb, Croatia, 2016.
4. Čarapina, M., Mekterović, I., Jagušt, T., Drljević, N., Baksa, J., Kovačević, P., Botički, I., "Developing a multiplatform solution for mobile learning," Proceedings of the 23rd International Conference on Computers in Education (ICCE 2015), Hangzhou, China, 2015, pp. 384–390.
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7. Macut, G., Drljevic, N., “Integration of Advanced Additional Capabilities to a Modern IPTV Platform: a Technical Study,” Proceedings of the 36th International Convention on Information & Communication Technology Electronics & Microelectronics (MIPRO), Opatija, Croatia, 2013, pp. 1258–1263.
8. Drljevic, N., Boticki, I., “Leveraging Social Networks to Increase Motivation in Learning Programming,” Proceedings of the 54th International Symposium ELMAR, Zadar, Croatia, 2012, pp. 341–344.
9. Boticki, I., Barisic, A., Martin, S., Drljevic, N., “Sortko: Learning Sorting Algorithms with Mobile Devices,” IEEE Seventh International Conference on Wireless, Mobile and Ubiquitous Technology in Education, Takamatsu, Japan, 2012, pp. 49–56.

14.3. Invited presentations at professional conferences

1. Drljević, N., “Successfully adapting to a new scenario for license negotiations”, Software Asset Management Strategies Europe (SAMS Europe), Copenhagen, Denmark, 2021.
2. Ancin A., Drljević, N., “Keynote: The matrix between SAM and IT Procurement – what benefits can be unlocked?”, Software Asset Management Strategies Europe (SAMS Europe), Berlin, Germany, 2020.
3. Drljević, N., “Closing Presentation: Implementing SAM in a European institution,” Software Asset Management Strategies Europe (SAMS Europe), Berlin, Germany, 2018.

15. ŽIVOTOPIS

Neven Drljević je europski dužnosnik, trenutno na poziciji voditelja Službe za upravljanje softverskom imovinom i imovinom u oblaku Europskog parlamenta. Rođen u Zagrebu 1985., diplomirao je računarstvo na Sveučilištu u Zagrebu Fakultetu elektrotehnike i računarstva (FER) (preddiplomski studij dovršen 2011., diplomski 2013.), specijalizirajući se za softversko inženjerstvo, upravljanje projektima i tehnologijom potpomognuto obrazovanje.

U profesionalnoj karijeri, nakon slobodnjačkih angažmana tijekom studija, zapošljava se kao asistent na Tehničkom veleučilištu u Zagrebu (TVZ) tijekom ak. god. 2013./2014. Dužnost u Europskom parlamentu započeo je u srpnju 2014., kao voditelj projekata zadužen za razvoj sposobnosti upravljanja softverskom imovinom Parlamenta, u sklopu Glavne uprave za inovacije i tehnološku podršku (DG ITEC). U lipnju 2018., delegacijom je zadužen za koordinaciju Službe za upravljanje individualnom opremom. U veljači 2020. promaknut je u voditelja novoosnovane Službe za upravljanje softverskom imovinom i imovinom u oblaku. Uz osnovnu dužnost, također ima dužnost dopisnika za zaštitu osobnih podataka za njegovu upravu unutar DG ITEC-a.

Usporedno sa razvojem profesionalne karijere, od 2013. polaznik je doktorskog studija računarstva na FER-u u modelu studija s dijelom radnog vremena, s fokusom istraživanja na obrazovna iskustva s proširenom stvarnošću, kao dijela tehnologijom potpomognutog obrazovanja. U sklopu studija, bio je koordinator za proširenu stvarnost u sklopu istraživačkog projekta SCOLLAm (2014. – 2017.)

Od 2012. do 2014. bio je član Savjeta mladih Grada Zagreba. Od 2013. do 2014. izabran je u Fakultetsko vijeće FER-a kao studentski predstavnik iz reda poslijediplomskih studenata.

Nagrađen je Posebnom rektorovom nagradom Sveučilišta u Zagrebu 2012., nagradom Ericsson Nikola Tesla (3. mjesto) 2012., nagradom Najbolji studentski računalni program FER-a (2. mjesto) 2012., nagradom za najbolji studentski rad na konferenciji MIPRO 2013. i, najnovije, Zahvalnicom DG ITEC-a 2019. za doprinose pripremama za 9. legislativni mandat u Europskom parlamentu.