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Existing Teaching Practices and Future Labour Market Needs in the Field of Augmented Reality

Analytical report

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Executive Summary

This report informs the community about the current teaching practices on topics related to Augmented Reality (AR) and associated industry needs. The report aims to raise awareness and allow for better decision-making within educational policies, in order to increase the number of high-qualified specialists prepared for AR-related tasks.

The goal of this report is to give higher education institutions and industry a broad view on the demands of the AR job market and provide them with recommendations on delivering innovative open educational programmes on AR, including approaches to teaching students about its various applications, which are increasingly in demand amongst European industries.

This report presents the analysis of existing courses in the field of AR in Part I, as well as an AR job market analysis in Part II.

The first part of this report contains the results of a study of AR teaching. In this study, we explore and review the current practices at the top-ranking universities of the world. It focuses on identifying and surveying universities in Europe and world-wide that have AR and related topics in their study programmes. The study investigates how AR teaching works in context. The major questions of the study include the methods used for teaching AR, types of learning activities, similarities and differences between AR learning activities. This review also provides information about content, objectives, entry requirements and learning outcomes of each identified AR course. Analysis of the results demonstrate that existing AR courses do not provide standardised teaching practices and methods of delivering information. Moreover, the content of these courses is not standardised. Learning outcomes of the reviewed courses do not have much in common with each other. The review of the existing teaching practices shows the need for a holistic and standardised course design that can deliver all necessary materials.

The second part of this report focuses on the Job Market analysis. We identified the essential skills for AR developers in industry through an open survey of specialists based on an analysis of job announcements in and related to the field. We report in detail on the results of the survey. The survey was targeted at organisations that recruit or plan to recruit AR specialists. Analysis of the results of the survey allowed us to identify the most important skills for future AR specialists. They include several concrete skills, such as knowledge of a specific AR SDKs (Unity, Vuforia) as well as an understanding of advanced programming topics like Artificial Intelligence, Object Recognition and Computer Vision. The identified skills can inform the AR course design and become major learning outcomes, since they are essential to the topic.

The survey of teaching practices and industry needs analysis aims to inform higher education policymakers and to guide partnerships' selection of learning methods, learning objectives, assessment criteria, and required knowledge, skills, and competences, filling the gap between formal education and the workplace.

This report summarises the work undertaken during the initial phase of the project Augmented Reality in Formal European University Education (AR-FOR-EU).

Introduction

AR is a rapidly growing market amongst the information and communication technologies. It provides an enriched view of the physical world, adding layers with contextually useful information, delivered visually or by stimulating other senses using wearable and hand-held devices (Fig. 1). AR is considered as a technology with a unique quality to provide a direct link between the physical reality and the virtual information about that reality[1]. Early applications of AR focused on games, but the possible commercial and educational applications of AR are almost unlimited.

Over the last few years AR has gained even more attention. Indeed, currently AR is largely used in medicine[2], manufacturing and engineering[3][4], education[5], construction[6], automotive[7], robotics[8], and aerospace industries[9], maintenance operations in various industries[10], and many other areas. The technology is currently being introduced in front-runner organisations, leading to an increasing demand for qualified specialists.

While the AR research and development community is growing stronger in Europe, the teaching competence and exchange of good practices in this field are still very fragmented. Educational offers for this topic in Europe are lagging, failing to produce the graduates (and numbers) required.

Rapid development of AR and related technologies and expanding area of their applications has led to the demand for highly qualified specialists in this field. While the AR research and development community is growing stronger, the teaching competence and exchange of good practices in this field are insufficient. There are examples of technology companies (e.g., Daqri[11], PTC[12] and Vuforia[13], Microsoft[14], Apple[15], Google[16]) teaching AR, because of the encountered difficulties in recruiting skilled personnel.

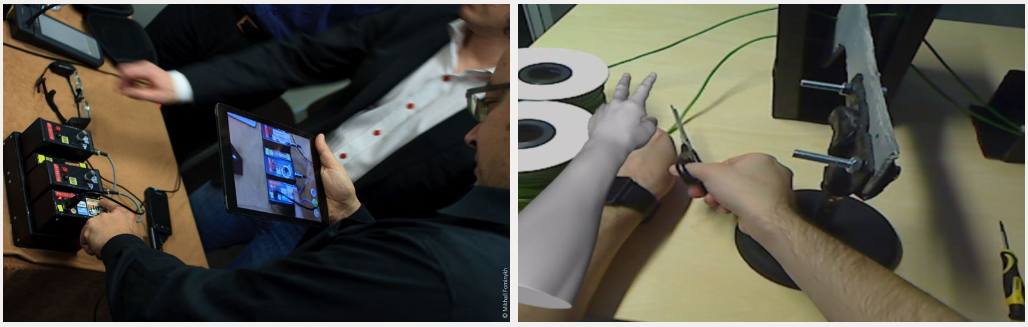


Figure 1.Examples of AR systems

[1] D. Schmalstieg and T. Höllerer (2016) 'Augmented Reality Principles and Practice'
[2] A. Meola (2016) 'Augmented reality in neurosurgery: a systematic review'
[3] A.Y.C. Nee et al. (2012) 'Augmented reality applications in design and manufacturing'
[4] H.L. Chi, S.C.Kang and X. Wang (2013) 'Research trends and opportunities of augmented reality applications in architecture, engineering, and construction'
[5] M. Akçayır and G. Akçayır (2017) 'Advantages and challenges associated with augmented reality for education: A systematic review of the literature'
[6] S. Zollmann (2014) 'Augmented Reality for Construction Site Monitoring and Documentation'
[7] A. Doshi (2017) 'Use of projector based augmented reality to improve manual spot-welding precision and accuracy for automotive manufacturing'
[8] D. Mourtzis, V. Zogopoulos and E. Vlachou (2017) 'Augmented Reality Application to Support Remote Maintenance as a Service in the Robotics Industry'
[9] K. Helin et. al (2017) 'Augmented Reality System for Space Station Maintenance Support'
[10] R. Palmarini (2017) 'A systematic review of augmented reality applications in maintenance'
[11] https://daqri.com/
[12] https://www.ptc.com/
[13] https://www.vuforia.com/
[14] https://www.microsoft.com/en-us/mixed-reality
[15] https://www.apple.com/lae/ios/augmented-reality/
[16] https://developers.google.com/ar/

Context

The report is done in the frame of the AR-FOR-EU project[17]. The Augmented Reality in Formal European University Education (AR-FOR-EU) project will establish and deepen a strategic partnership for teaching AR in Higher Education at scale on undergraduate and graduate levels. AR-FOR-EU brings together five internationally renowned institutions to reflect their research, development and teaching expertise into a validated course offer of excellence, extended with rich and professionally produced open course materials.

AR-FOR-EU will help improve quality of educational programs by creating a new offer in an area conducive to Europe's global competitiveness, with technology uptake already showing positive effects in a variety of industrial fields. It will do so by collecting expertise at the European and international levels to create a foundation for teaching AR in formal education, preparing professionals for the industries of tomorrow and contributing to making European economies more research-driven, knowledge-based, and competitive.

AR-FOR-EU sets its objectives as:

- to support capacity building of new and emerging digital skills for AR
- produce two innovative courses on AR
- create a strategic partnership to promote excellence in teaching
- design technology-based and pedagogically sound digital Open Educational Resources and online courses for a Massive Online Open Course platform aimed at opening up and fostering uptake across Europe.

[17] http://codereality.net/

Part I. Existing Teaching Practices in the Field of AR

Key AR enabling technologies are becoming more and more affordable for the customer, which means companies need to produce more software and content and acquire more skilled professionals in the field of AR. This whole pipeline leads to the necessity of increasing the number of educational courses on the topic of AR.

Santos and Dias[18] refer to the first set of recommendations for courses of AR and virtual reality (VR) described by the European Association of Virtual and Augmented Reality in 2008. According to their study, the training course should last at least 32 hours with topics, including but not limited to principles of computer graphics in VR, perception, human factors, interaction in VR, hardware, software, mixed reality and applications of AR/VR, etc. Due to the fast growth of the AR market, maintaining the appropriate pedagogy in unison with the uptake of the technology is difficult and the corresponding lack of professionals can lead to the stagnation of the AR domain.

Our analysis of existing courses shows how the field of AR education is fragmented, the teaching competence and exchange of good practices does not exist to produce the graduates to fit the requirements of industry. This report outlines problems and highlights advances in existing AR courses. Based on this information competent, well-structured and market-satisfying AR courses can be designed.

1 Methodology

1.1. Identification of Educational Programs and Courses

The process of data selection included a search for master's degree programs and courses related to AR. The following databases were used as sources:

- Studyportals masters[19]
- Studyportals bachelor[20]
- FindAMasters[21]

In order to assess teaching methods and existing practices of AR education, we also looked for scientific papers and through websites of the world leading universities.

1.2. Inclusion and Exclusion Criteria

In the study, we used the following inclusion criteria:

- We considered only programs and courses on the topic of AR i.e. those that teach AR and not use applications of AR for teaching other domains.
- In our survey we considered only high ranked universities: top 400 in 2018 in the following rankings:
- Times Higher Education World University Rankings[22]
- QS World University Rankings[23]
- Academic Ranking of World Universities (Shanghai Ranking)[24]
- Criteria for scientific papers: publication not later than 5 years, paper indexed in WoS or Scopus.

[18] B. Sousa Santos and P. Dias (2017) 'What Should a Virtual/Augmented Reality Course be'
[19] https://www.mastersportal.com/
[20] https://www.bachelorsportal.com/
[21] https://www.findamasters.com/

1.3. Key Words

For the research, we simply used the search term: "augmented reality". We later added another search term "virtual reality". It allowed us to discover additional courses that include AR topics. We did not consider VR-only courses.

When searching for scientific papers, we used two additional terms: "education" and "courses".

1.4. Extracting Data

As mentioned, the process of data selection included a search for educational degree programs related to AR in two major databases (Studyportals and FindAMasters) by the defined search terms.

The overall search results gathered from these databases are shown in Table 1. A review of the titles helped to eliminate duplicate programs, as some of them were listed in both databases.

Table 1. Sources of Data Gathering

Source	Search Strings		Total
	Virtual Reality	Augmented Reality	
Studyportals (master)	148	59	206
FindAMasters	112	40	152
Studyportals (bachelor)	170	47	217

The detailed descriptions of programmes that matched the search query were extracted from the databases. Their objectives and course content were carefully read in order to remove those programmes that do not include AR.

As a result, a list of 19 courses from 15 universities were obtained for the final analysis. The rest of the courses were disqualified due to their low ranking or lack of focus on AR.

[22] https://www.timeshighereducation.com/world-university-rankings/2018/world-ranking#!/page/0/length/25/sort_by/rank/sort_order/asc/cols/stats
[23] https://www.topuniversities.com/university-rankings/world-university-rankings/2018
[24] http://www.shanghairanking.com/ARWU2018.html

1.5. Data Coding and Analysis Process

For data collection we used official university web pages with the description of educational programs as most of them have provided syllabi along with detailed information.

The information was grouped in accordance with the following categories:

- Number of credits
- Program title (subject area) that contains a course
- Prerequisites and course type (core/elective)
- Objectives
- Learning outcomes
- Content
- Teaching methodology
- Assessment criteria

In the next section, we present a list of courses with information grouped according to the categories mentioned above.

2 Results and Analysis

As mentioned earlier, one of the criteria for the final list selection was the rank of the Higher Education Institution where the course or programme was delivered. Table 2 presents the list of universities and their positions in the QS World University ranking, Times Higher Education World University Rankings, and Academic Ranking of World Universities.

The only university, which was not in the top 400 was the University of Bradford, however, we decided to include it as it provides a very relevant BSc (Hons) in Virtual and Augmented Reality.

Table 2. List of Universities

#	Higher Education Institution	Country	QS #	THE #	ARWU #
1	Aalto University	Finland	101-150	99 (190)	401-500
2	TU Wien	Austria	51-100	126-150	101-150
3	Technical University of Munich	Germany	64	41	50
4	Trinity College Dublin	Ireland	88	117	151-200
5	University of Cambridge	UK	5	2	3
6	National University of Singapore	Singapore	15	22	91
7	City University of Hong Kong	China	49	119	201-300
8	Carnegie Mellon University	USA	47	24	80
9	Cornell University	USA	16	19	13
10	Johns Hopkins University	USA	17	17	16
11	University of California Berkeley	USA	27	18	5
12	University of Bradford	UK	601-650	601-800	-
13	Tilburg University	Netherlands	357	195	-
14	Columbia University	USA	18	14	8
15	Stanford University	USA	2	3	2

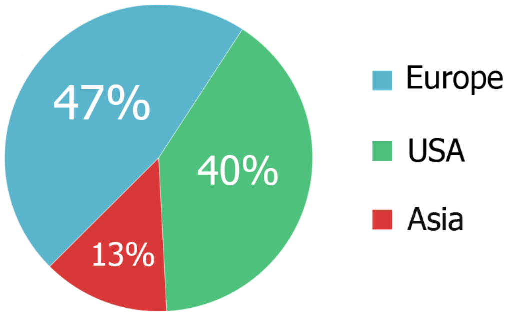


Figure 2.Distribution of AR Courses by Region

From the Tables 2 and Figure 1, it appears that most of the universities are situated in the United States of America and Europe (primarily in United Kingdom). Together they present almost a half of all universities. It shows how niche the subject is, and that AR-courses are not yet settled down in the academic space. It reaffirms the need in a holistic approach to the design of courses on AR.

2.1. Certification and Validity

Table 3. Certification and Validity

#	Higher Education Institution	Course title	Credits[25]	Course validity
1	Aalto University	Virtual and Augmented Reality	5 ECTS = 135 study hours	Last offering: Spring 2017/18
2	TU Wien	Module Virtual Reality and Augmented Reality	9 ECTS = 225 study hours	Currently active
3		Virtual and Augmented Reality	2 ECTS = 30 study hours	Currently active
4		Introduction to Virtual and Augmented Reality	N/A	Currently active
5	Technical University of Munich	Augmented Reality	6 ECTS = 180 study hours	Currently active
6		Medical Augmented Reality	5 ECTS = 150 study hours	Currently active
7	Trinity College Dublin	Augmented Reality	5 ECTS = 125 study hours	Currently active
8	University of Cambridge	Mobile App Building and Augmented Reality: An Introduction	Two half day sessions	Last offering: March 2018
9	National University of Singapore	Interaction Design for Virtual and Augmented Reality	4 MC = 6.68 ECTS = 180 study hours	Currently active
10		Mobile Interaction Design	4 MC = 6.68 ECTS = 180 study hours	Currently active
11	City University of Hong Kong	Image Processing and Augmented Reality	3 credit units = 6 ECTS = 162 study hours	Last offering: 2016/17
12	Carnegie Mellon University	Designing Computer Vision Apps	12 university units = 192 working hours	Last offering: Spring 2016/17

[25] All credits were calculated in the number of study hours corresponding to the country's ECTS conversion or university rules.

13	Cornell University	Virtual and Augmented Reality	3-month course (no. of credits is unknown)	Last offering: Autumn 2017/18
14	Johns Hopkins University	Augmented Reality	3 credits = 45 study hours	Last offering: Spring 2017/18
15	University of California Berkeley	Augmented and Virtual Reality	2 days	Last offering: May 2018
16	University of Bradford	Augmented Reality Design: Principles and Practice	20 credits = 200 study hours	Currently active
17	Tilburg University	Virtual and Augmented Reality	6 ECTS = 168 study hours	Currently active
18	Columbia University	3D User Interfaces and Augmented Reality	3 points = 135 study hours	Last offering: Spring 2017/18
19	Stanford University	Human-Computer Interaction: Issues in Mixed and Augmented Reality	3-month course (no. of credits is unknown)	Last offering: 2015/16

Note: University College London provides a full 1-year master program in VR, nonetheless this program does not contain any concrete AR courses, but contains some AR-related topics such as: Image Processing, Computational Photography and Capture.

Note: Most of the selected courses last longer than 150 hours, which shows that the AR field has a lot of material to be covered. Although some of the courses are designed as a short (usually 2-days) working session, they work like additional classes and aim at familiarising students with the AR topic in general. These are the courses of University of Berkeley and University of Cambridge.

2.2. Programmes that Contain AR Courses

A provisional analysis of the results indicates that the identified courses relate to different fields of study and belong to different study programs. We group some of them into clusters. The distribution of the subject areas is listed in the table 4.

Table 4. Subject Areas

#	Subject area	Program title[26]	Number of programs
1	Media	Communication and New Media, Creative Media, Media Technology, Multimedia Design, Visual Computing, Computer Graphics	6
2	Computer Science	Computational Science, Information Systems, Information Technology, Computer Science	5
3	Game design	Game Design, Interactive Entertainment	2
4	Health	Biomedicine, Health Informatics	2
5	Virtual and Augmented reality	Virtual and Augmented Reality	2
6	Artificial Intelligence	Artificial Intelligence	1

[26] Titles of educational programs which host AR courses

The distribution presented in Table 4 indicates that most of the other courses work belong to Media or Computer Science programmes. There are only two courses that are part of programmes focused on AR and VR technology.

We can conclude that AR is not yet acknowledged as a standalone field of study and therefore is currently considered as a supporting course or a component mostly for Computer Science and Media Technology programs.

2.3. Course Types and Prerequisites

Prerequisites are an essential characteristic of educational programs or educational course as they help lecturers to teach at a certain academic level and the students to be confident with their chosen courses. Prerequisites also help to define the target audience for a course.

According to international educational practice, study programs include core and elective courses of study. Core course of study, also called core curriculum, refers to a series or selection of courses that all students are required to complete before they can move on to the next level in their education or earn a diploma[27]. Elective course (or electives) could be chosen from a list of optional courses that students choose to take according to their interests.

Table 5. Course Types and Entry Requirements

#	Course title	Course title	Core or elective	Entry requirements
1	Aalto University	Virtual and Augmented Reality	N/A	At least basic programming skills for scripting with Unity, knowledge on 3D computer graphics and user interaction are also of advantage.
2	TU Wien	Module Virtual Reality and Augmented Reality	Core	Not mentioned
3		Virtual and Augmented Reality	Core	Not mentioned
4		Introduction to Virtual and Augmented Reality	N/A	Not mentioned
5	Technical University of Munich	Augmented Reality	Elective	Linear Algebra for Informatics, Basic mathematical and programming skills. Fundamentals of Algorithms and Data Structures
6		Medical Augmented Reality	Elective	Not mentioned
7	Trinity College Dublin	Augmented Reality	Elective	Background in fundamentals of computer vision and graphics will be helpful but not necessarily required.
8	University of Cambridge	Mobile App Building and Augmented Reality: An Introduction	N/A	Attendees should be confident computer users, comfortable with editing HTML documents, and experienced with publishing pages on a web server.

[27] https://www.edglossary.org/core-course-of-study/

				Attendance of the Programming Concepts: Introduction for Absolute Beginners or equivalent knowledge
9	National University of Singapore	Interaction Design for Virtual and Augmented Reality	N/A	CS3240 (Interaction design) and MA1301 (Introductory mathematics) or A-level / H2 Mathematics)
10		Mobile Interaction Design	Elective	Having a background in Unity Programming will be helpful but not required. You will learn it in the course.
11	City University of Hong Kong	Image Processing and Augmented Reality	Elective	None
12	Carnegie Mellon University	Designing Computer Vision Apps	Elective	No prior knowledge of computer vision or machine learning is required although a strong programming background is a must (at a minimum good knowledge of C/C++)
13	Cornell University	Virtual and Augmented Reality	Elective	Not mentioned
14	Johns Hopkins University	Augmented Reality	N/A	Linear Algebra, Data Structures, Intermediate Programming
15	University of California Berkeley	Augmented and Virtual Reality	N/A	None
16	University of Bradford	Augmented Reality Design: Principles and Practice	Core	GCSE English and Mathematics at grade C or 4 (equivalents accepted). Minimum IELTS at 6.0 or the equivalent.
17	Tilburg University	Virtual and Augmented Reality	Elective	Data Processing or Programming with R (programming language)
18	Columbia University	3D User Interfaces and Augmented Reality	Elective	COMS W4160 (Computer Graphics), or COMS W4170 (User Interface Design), or a strong desire to learn about 3D user interfaces and permission of the instructor.
19	Stanford University	Human-Computer Interaction: Issues in Mixed and Augmented Reality	N/A	Not mentioned

From Table 5 above we can see that most of the programs that were selected for the analysis do not have strong prerequisites or entry requirements. Notably, they do not require previous experience in AR (or VR) to take the classes. As can be seen from the same table, the number of electives courses is higher than the number of core courses.

However, students should have at least basic mathematical and programming skills (depending on the university it could be Python or Java, C or C++, Unity programming or equivalent), linear algebra, especially with respect to 3D transformations, fundamentals of algorithms and data structures.

As mentioned in some programme syllabi, knowledge of 3D computer graphics, user interaction or some background in fundamentals of computer vision will be helpful but are not necessarily required.

At the same time, some courses, for example a course in Virtual Reality by Stanford University requires strong programming experience (especially JavaScript, C or C++). In addition, course homework requires JavaScript and GLSL programming. Even though they do not assume prior experience in JavaScript and GLSL, students should be able to understand object-oriented programs and modify them. Moreover, previous knowledge of computer graphics or computer vision is mentioned as helpful but is not required.

2.4. Educational Programmes

Our review also indicates that the core courses are normally a part of educational programs with more specific learning objectives. These programs are:

- MSc in Visual Computing module of the program at TU Wien
- MSc in Visual Computing core course of the program at TU Wien
- BSc in Virtual and Augmented Reality at University of Bradford

Table 6. Study Programs that Include AR Courses

#	Higher Education Institution	Course title	Study programmes
1	Aalto University	Virtual and Augmented Reality	MSc Pr. Game Design and Production
2	TU Wien	Module Virtual Reality and Augmented Reality	Programme in Visual Computing
3		Virtual and Augmented Reality	MSc program in Visual Computing
4		Introduction to Virtual and Augmented Reality	N/A
5	Technical University of Munich	Augmented Reality	BSc/MSc in Informatics BSc/MSc in Games Engineering MSc in Computational Science and Engineering BSc/MSc in Information Systems
6		Medical Augmented Reality	MSc in Biomedical Computing
7	Trinity College Dublin	Augmented Reality	MSc in Interactive Entertainment Technology
8	University of Cambridge	Mobile App Building and Augmented Reality: An Introduction	N/A
9	National University of Singapore	Interaction Design for Virtual and Augmented Reality	MSc in Computer Science

10		Mobile Interaction Design	MSc in Communications and New Media
11	City University of Hong Kong	Image Processing and Augmented Reality	BSc in Arts and Science in New Media
12	Carnegie Mellon University	Designing Computer Vision Apps	BSc in Computer Science
13	Cornell University	Virtual and Augmented Reality	MSc in Information Systems, Connective Media
14	Johns Hopkins University	Augmented Reality	Not mentioned
15	University of California Berkeley	Augmented and Virtual Reality	N/A
16	University of Bradford	Augmented Reality Design: Principles and Practice	BSc in Virtual and Augmented Reality
17	Tilburg University	Virtual and Augmented Reality	MSc in Cognitive Science and Artificial Intelligence
18	Columbia University	3D User Interfaces and Augmented Reality	BSc in Computer Science
19	Stanford University	Human-Computer Interaction: Issues in Mixed and Augmented Reality	BSc/MSc in Computer Science

2.5. Meeting Curriculum Objectives and Skill Development

Tables 4 and 5 below present general objectives of the courses selected for the analytical review. As illustrated, most of the courses introduce students to the field of AR. They aim to provide fundamental knowledge and state-of-the-art in this subject, as well as practical aspects of AR solutions. Some courses also provide both technological and human aspects of AR.

There are courses, that give more specific knowledge, for example:

- "This course introduces students to the field of AR. It reviews its basic definitions, principles and applications. This course introduces students to the field of AR. It then focuses on Medical AR and its particular requirements" (Augmented Reality, Johns Hopkins Whiting school of engineering).
- "The objectives of this lecture are to have students learn the theoretical basics and practical aspects of AR solutions related to the medical field" (Augmented Reality, TU of Munich).

Table 7. General Objectives of Courses that Include Mostly AR Topics

#	Higher Education Institution	Course title	Key Aspects	Objectives
1	TU of Munich	Augmented Reality	MSc Games Engineering, MSc Computational Science and Engineering, MSc Information Systems	Main purpose of the course is to enable students to analyse the underlying mathematical and programming aspects of AR systems, apply skills in own further-reaching solutions, evaluating existing input and output devices regarding their suitability for special application scenarios[28].
2		Medical Augmented Reality	Teaching as a part of Biomedical Computing	The objectives of this lecture are to have students learn the theoretical basics and practical aspects of AR solutions related to the medical field[29].
3	Trinity College Dublin	Augmented Reality	MSc in Interactive Entertainment Technology	This course will cover fundamentals and state-of-the-art in AR, as well as related areas of 3D computer vision and graphics[30].
4	University of Cambridge	Mobile app building and AR: an Introduction	Training course for university members	This introduction to building mobile apps explores the basic elements and options for an app, from the simpler menu-driven and webpage rendering approaches, to some of the possibilities involved in orientation and location-sensitive data inputs and AR techniques[31].
5	National University of Singapore	Mobile interaction design	MSc in Communications and New Media	This module addresses the growth of mobile AR and the move of computing away from the desktop and into everyday lives, activities, and environments. [...] Students in this course will explore the theory and practice of such relevant concepts as situatedness, context, and mobile media in the context of designing for mobile AR platforms[32].
6	Johns Hopkins Whiting school of engineering	Augmented Reality	Focuses on Medical AR and its requirements.	This course introduces students to the field of AR. It reviews its basic definitions, principles and applications. It then focuses on Medical AR and its particular requirements[33].

28 https://campus.tum.de/tumonline/wbModHBReport.wbGenHTMLForBeschr?pKnotenNr=456372&pSemesterNr=175&pLangCode=EN

29 https://campus.tum.de/tumonline/wbModHBReport.wbGenHTMLForBeschr?pKnotenNr=456372&pSemesterNr=175&pLangCode=EN

30 https://www.scss.tcd.ie/modules/?m=CS7GV4

31 https://www.training.cam.ac.uk/event/2233473

32 https://ivle.nus.edu.sg/V1/lms/public/view_moduleoutline.aspx?CourseID=3DDEC613-8114-4DC0-9AA0-38FFBF27F388&ClickFrom=StuViewBtn

33 https://camp.lcsr.jhu.edu/course/

7	City University of Hong Kong	Image Processing and Augmented Reality	Part of Bachelor of Arts in Creative Media: Bachelor of Arts and Science in New Media	The course aims to provide fundamental knowledge in digital image processing and its applications in pixel based computer graphics. The classes introduce the theory and practical tools to create, manipulate and display digital images with the use of simple computer programming[34].
8	University of Bradford	Augmented Reality Design: Principles and Practice	Course of Bachelor of Virtual and Augmented Reality	This module is an introduction to augmented reality and aims to equip students with relevant knowledge, understanding and expertise and will plan, design and develop applications intended for use in real and public spaces[35].
9	Carnegie Mellon University	Designing Computer Vision Apps	Bachelor of science in computer science	This course is aimed at covering concepts associated with the emerging topic of applying computer vision to app development on smart devices and embedded devices[36].
10	Columbia University	Human-Computer Interaction: Issues in Mixed and Augmented Reality	Part of MSc of Computer Science	In this course, students engage with a range of issues around design and development of MR systems and develop their own MR interactions. Students work in project teams, prototyping their concept and communicating their progress through demonstration, final report, and presentation[37].

Table 8. General Objectives of Courses that Include both AR and VR Topics

#	Higher Education Institution	Course title	Key Aspects	Objectives
1	Aalto University	Virtual and Augmented Reality	Part of MSc Pr. Game Design and Production	[…] both technological and human aspects of VR and AR […], including visual and auditory displays, psychophysiology of senses, user tracking and other input techniques, and building practical applications[38].
2	TU Wien	Module on Virtual Reality und Augmented Reality	Part of the programme in Visual Computing	This module provides a comprehensive overview of the main areas of computer graphics: rendering, visualisation, augmented and virtual reality, visual analytics.
3		Virtual and Augmented Reality	Part of MSc program in Visual	This course introduces to Virtual and Augmented Reality[39].

[34] http://www.cityu.edu.hk/catalogue/ug/201617/course/SM3123.htm
[35] https://www.bradford.ac.uk/media-v8/aqeo/modules/2019-20/GAV5023-B_AugmentedRealityDesignPrinciplesAndPractice201920.pdf
[36] http://16423.courses.cs.cmu.edu/
[37] http://www.cs.columbia.edu/~feiner/courses/csw4172/
[38] https://oodi.aalto.fi/a/opettaptied.jsp?MD5avain=&Kieli=6&OpetTap=1130236691&takaisin=vl_kehys.jsp&Ilmoit=0&vl_tila=2&Opas=10798&ooo_SortJarj=2&Org=502030&haettuOpas=10798
[39] https://tiss.tuwien.ac.at/course/courseDetails.xhtml?dswid=6432&dsrid=432&courseNr=188369&semester=2017W

			Computing	
4		Introduction to Virtual and Augmented Reality	N/A	Conduct basic and application-oriented research in all areas related to virtual and augmented reality[40].
5	National University of Singapore	Interaction design for virtual and augmented reality	Part of MSc of Computer Science	This module aims to expose students to the human-cantered principles of designing and building VR and AR applications[41].
6	Cornell University	Virtual and Augmented Reality	Part of MSc Information Systems, Connective Media	This course presents an introduction to this exciting area, with an emphasis on designing and developing virtual and AR applications[42].
7	University of California, Berkeley	Augmented and Virtual Reality	N/A	[…] understanding and familiarity of key industry terms and trends, address how these trends can impact your business and explore opportunities for new products, services or ventures for your business[43].
8	Tilburg University	Virtual and Augmented Reality	Part of MSc Cognitive Science and Artificial Intelligence	In this multidisciplinary course, we approach VR and AR both from a practical and theoretical perspective[44].
9	Stanford University	HCI Issues in Mixed and Augmented Reality	Part of MSc Computer Science	In this course, students engage with a range of issues around design and development of MR systems and develop their own MR interactions[45].

40 https://www.ims.tuwien.ac.at/projects/vr-course
41 https://ivle.nus.edu.sg/V1/lms/public/view_moduleoutline.aspx?CourseID=06C4D3A7-D2FF-4A67-A7C5-6E9EC32D910B&ClickFrom=StuViewBtn
42 http://courses.cornell.edu/preview_course_nopop.php?catoid=31&coid=501601
43 http://exec-ed.berkeley.edu/courses/arvr/
44 https://mystudy.uvt.nl/it10.vakzicht?taal=N&pfac=FGW&vakcode=880006
45 https://web.stanford.edu/class/cs377m/schedule.html

From Tables 7 and 8, we can see that objectives and the contents of these courses are highly diverse, some courses focused more on the technical implementation of AR while others focused on design principles of AR applications. Some of these courses even look at AR from a business point of view.

We should point out that many courses focus much on the theoretical introductory aspect of the AR field. Analysing differences in the selected courses, can facilitate the design of a comprehensive course, which may include the following topics:

- Short theoretical introduction to the AR field
- Interaction design methodologies
- Full development cycle of AR applications
- AR specific and supporting technologies: Vuforia, Holo toolkit, Unity
- Machine learning and AI for data visual analysis
- Hardware (platform) specific requirements
- Design and production of AR wearables

We can extract two important conclusions from these analyses:

- AR domain has a lot of material to be taught. And this material can be split in different ways to categories: theoretical-practical, basic-advanced, media-computer science, etc…
- It all supports the idea of necessity in having a holistic view on AR educational courses that can fit in all necessary information about this technology and associated pedagogy.

2.6. Learning Outcomes

"Learning outcomes are sets of competences, expressing what the student will know, understand or be able to do after completion of a process of learning, long or short"[46].

Learning outcomes focus on what the student has achieved rather than merely focusing on the content of what has been taught[47].

Core Skills

The following table provides an overview of learning outcomes in the selected AR courses (Table 9). Courses without information about learning outcomes that were omitted from this table.

Table 9. Learning Outcomes of AR Courses

#	Higher Education Institution	Course title	Learning outcomes
1	TU of Munich	Augmented Reality	▪ Describe and analyse the underlying mathematical and programming aspects (tracking and rendering) of AR systems extend them towards own, further-reaching solutions ▪ Evaluate existing input and output devices regarding their suitability for special application scenarios
2	TU of Munich	Medical Augmented Reality	▪ Knowledge of the theoretical basics and practical aspects of AR solutions related to the medical field

[46] European Commission (2004) 'European Credit Transfer and Accumulation System': http://ec.europa.eu/dgs/education_culture/publ/pdf/ects/en.pdf
[47] D. Kennedy (2007) 'Writing and Using Learning Outcomes: A Practical Guide'.

3	Trinity College Dublin	Augmented Reality	▪ Review and assess the state-of-the-art in augmented reality technologies ▪ Develop an augmented reality solution (project) including implementation, testing, evaluation, demonstration, and documentation ▪ Come up with own ideas for an augmented reality project
4	University of Cambridge	Mobile app building and AR: an Introduction	▪ Create mobile application that can support the possibilities of orientation and location-sensitive data inputs and augmented reality techniques
5	National - University of Singapore	Mobile Interaction Design	▪ Participate in the research agenda of designing for mobile Augmented Reality interaction
6	City University of Hong Kong	Image Processing and Augmented Reality	▪ Identify key concepts in pixel based computer graphics and simple image processing techniques ▪ Apply the image processing techniques to generate creative computer graphics ▪ Describe simple computer vision mechanisms and motion tracking applications ▪ Relate computer vision techniques in human computer interaction application areas ▪ Associate, combine and integrate knowledge from different disciplines (e.g. mathematics, sciences, literature etc.) into course assignments ▪ Transform basic technical competence into a unique style or personal signature
7	Carnegie Mellon University	Designing Computer Vision Apps	▪ Come up to speed rapidly with the latest in environments, software tools and best practices for developing computer vision app

The analysis of learning outcomes in the selected AR courses (Table 9) indicates that students, who successfully complete courses in AR, should be able to demonstrate both theoretical and practical competencies and skills.

Nevertheless, not all courses provide a unified set of skills. While some programmes focus on the application of AR in the medical domain, others aim to develop skills in mathematics and low-level programming. This indicates how current educational offerings in the field of AR lack a standardised list of skills that students should acquire.

Comparing learning outcomes of this table and with the results of our job market survey (Part II of this report), we can see that most of the existing courses do not provide the full list of competencies required in the most job announcements.

Existing courses focus either on low-level aspects of AR, such as image recognition, tracking and visual computing, or on application development and high-level programming languages specific for AR. In order to fulfil all possible requirements of the job market, an AR course should contain both parts.

Cognitive and Soft Skills

Apart from theoretical competencies, attention is also paid to so-called soft skills, such as the ability to work as a team, problem solving and project management.

For example, on successful completion of an AR course at Trinity College Dublin, students must be able to "come up with new ideas for an augmented reality project". To learn how to work as a team, students will create their own project and complete all stages of the project lifecycle, in particular, they must come up with an idea and then implement, test, evaluate and demonstrate. A similar task is implemented through a training course at the University of California, Berkeley, "through a mentored project, students will create and build a plan to enter this new market [Augmented Reality]".

Analysing the selected courses and their learning outcomes, we identified several recurring, cognitive and soft skills. Assessment methods of the selected courses also point towards cognitive and soft skills. For example, almost every course mentions a collaborative project as a final task, and therefore ability to work as a team and project management skills are important. Self-responsibility and self-organisation are also necessary, as many courses require a completed solo-project from each student.

The following cognitive and soft skills that are essential learning outcomes for an AR course:

- Understanding current research and publications in selected field
- Conducting your own research project in a selected area
- Critical thinking
- Ability to work as a team
- Project management
- Self-organisation, self-responsibility
- Communication and criticism

2.7. Teaching Methods

All courses selected for the analysis are delivered through a mixture of different teaching methods such as lectures, laboratory work, tutorials and project work. This combination of teaching methods differs from one course to another. We accumulated all teaching practices, types of interaction and assessment methods used in AR only focused courses. All information was taken from the course description pages and curriculum documents.

Course Focus

Almost all the courses selected for the analysis provide only an introductory level of understanding AR. We can categorise all these courses based on their primary focus:

- Low-level aspects of AR-technology
- Production of AR apps using existing engines and programming libraries
- Domain-specific application of AR
- Theoretical review of existing AR apps and AR techniques

Learning Interaction Types

All courses selected for the analysis that last longer than two classes, contain a basic set of activities: lectures and practical seminars or lab hours. In Table 10 below, we present the types of learning activities primarily used in the courses. We left out courses for which we could not find concrete information about the types of activities applied.

Table 10. Interaction Types in AR Courses

#	Higher Education Institution	Course title	AR or VR/AR	Interaction types
1	Aalto University	Virtual and Augmented Reality	VR/AR	▪ Lecture ▪ VR Lab - can be used during study project development and to showcase student's projects, as well as for research purposes.
2	TU of Munich	Augmented Reality	AR	▪ Lecture ▪ Tutorial (voluntary) - classes for discussing solutions of previous assignments
3		Medical Augmented Reality	AR	▪ Lecture ▪ Exercise class - Implementation of lecture course topics with students in groups of 2.
4	Trinity College Dublin	Augmented Reality	AR	▪ Lecture ▪ Lab
5	University of Cambridge	Mobile app building and AR: an Introduction	AR	▪ Two-days lectures session
6	National University of Singapore	Mobile Interaction Design	AR	▪ Workshop
7		Interaction Design for Virtual and Augmented Reality	VR/AR	▪ Lecture ▪ Guided Lab ▪ Unguided Lab (optional)
8	City University of Hong Kong	Image Processing and Augmented Reality	AR	▪ Lecture ▪ Workshop ▪ Project presentation (several classes over the course)
9	Carnegie Mellon University	Designing Computer Vision Apps	AR	▪ Lecture
10	Johns Hopkins Whiting school of engineering	Augmented Reality	AR	▪ Lecture ▪ Tutor class (meeting with the tutor about personal course project)
11	University of California, Berkeley	Augmented and Virtual Reality	VR/AR	▪ Lecture
12	University of Bradford	Virtual and Augmented Reality	AR	▪ Lecture ▪ Seminar ▪ Project Supervision ▪ Lab
13	Tilburg University	Virtual and Augmented Reality	VR/AR	▪ Seminars ▪ Practice
14	Columbia University	3D User Interfaces and Augmented Reality	AR	▪ Lecture
15	Stanford University	HCI Issues in Mixed and Augmented Reality	VR/AR	▪ Lecture

Almost every course ends with a collaborative or an individual project that students are expected to develop during the course. In some courses, students are provided with laboratory environment to develop, test and present their projects.

The combination of teaching methods differs from one course to another, depending on the primary focus of the course and other factors. For example, in the Medical AR course at the TU of Munich, lecture blocks are followed by an exercise block the following week. In the Augmented Reality course at the Trinity College Dublin, students follow two lecture hours and 1 lab hour on a weekly basis. An interesting method is used in the Mobile Interaction Design course at the National University of Singapore, where educators "adopt a workshop-type class facilitation method with minimal slides. Instead, it will be up to students to drive the conversation, and adapt to new information as the discussion moves along".

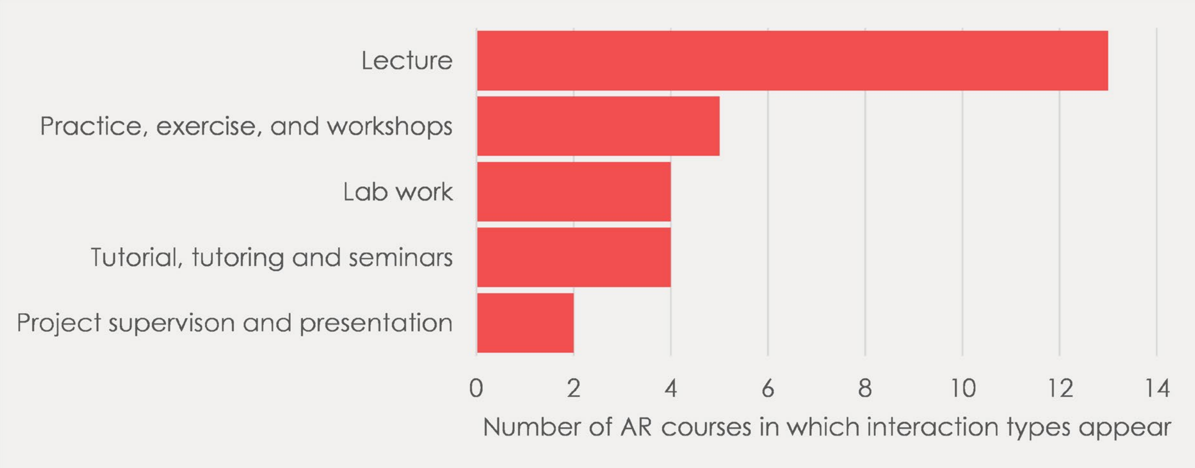


Figure 3.Interaction types

Our analysis demonstrates that AR is treated just like any other common practical IT course (Fig. 3). Moreover, most of the courses selected for the analysis use traditional lectures are as the main interaction type (Table 10 and Fig. 3). The only specific difference in some courses is that the students are provided with access to AR/VR laboratories due to the technology requirements.

At the same time, some subjects do have specific teaching methods (find examples in Human-Computer Interaction, wearable technology, etc).

We can see that currently there are no specific teaching approaches in AR courses. The lack of topic-specific teaching methods in AR represents a gap in the knowledge and an opportunity for higher education.

Assessment Methods

Assessment is one of key components of the learning process, as it allows students to demonstrate their understanding of the subject. It is essential for the course instructor to know whether the educational goals and standards of the lessons were met.

There are different types of assessment, including traditional methods such as examination, assignments, coursework, as well as new methods like peer ranking.

Table 11. Assessment Methods in AR courses

#	Higher Education Institution	Course title	AR or VR/AR	Assessments
1	Aalto University	Virtual and Augmented Reality	AR/VR	▪ Homework assignments ▪ Exam
2	TU Wien	Introduction to Virtual and Augmented Reality	AR/VR	▪ Assignments
3	TU of Munich	Augmented Reality	AR	▪ Assignments (voluntary) ▪ Team project (final project) ▪ Written exam (test)
4		Medical Augmented Reality	AR	▪ Written exam at the end of the course
5	Trinity College Dublin	Augmented Reality	AR	▪ Solo project
6	University of Cambridge	Augmented Reality	AR	▪ Coursework (project)
7	National University of Singapore	Mobile Interaction Design	AR	Individual component ▪ Individual homework/tutorial assignment ▪ Online forum activity - Submit thoughts, requests for help, or solutions to other people's problems ▪ Experiment Participation - administer your own experiment/user study for your project Group component ▪ Group project (working Prototype, project video report and peer ranking)
8		Interaction Design for Virtual and Augmented Reality	VR/AR	▪ Assignment ▪ Class participation ▪ 2-3 Assignments as mini-projects ▪ Group project ▪ Final Exam
9	City University of Hong Kong	Image Processing and Augmented Reality	AR	▪ In-class programming exercises
10	Carnegie Mellon University	Designing Computer Vision Apps	AR	▪ Assignments ▪ Solo project
11	Cornell University	Virtual and Augmented Reality	VR/AR	▪ Course Project
12	Johns Hopkins Whiting school and engineering	Augmented Reality	AR	▪ Assignments ▪ Projects ▪ Final Exam ▪ Class participation ▪ Mock-up Exam Submission
13	University of	Virtual and Augmented	AR	▪ Summative assessment: Presentation of the coursework

	Bradford	Reality		▪ Coursework prototype ▪ Coursework paper
14	Tilburg University	Virtual and Augmented Reality	VR/AR	▪ Presentation ▪ Group project - research pilot & article ▪ Short tests
15	Columbia University	3D User Interfaces and Augmented Reality	AR	▪ Individual assignments ▪ Team project
16	Stanford University	HCI Issues in Mixed and Augmented Reality	VR/AR	▪ Assignments ▪ Group Assignments ▪ Group Project

The analysis indicates that there are some courses where only one assessment method is used. For example, the course in Virtual and AR in TU Wien, and the Medical Augmented Reality in TU of Munich. In first case, a written exam is used as a tool for student assessment, while in the second case classic assignments are used. The course in AR from Trinity College Dublin also use a single assessment tool, but a project rather than an exam: "Students will be asked to design their own project (individual or groups) from idea to implementation, testing, evaluation, demonstration and documentation."

Mobile Interaction Design course at the National University of Singapore uses different assessments methods, such as participation on the course online forum and peer ranking of group projects: "Submit your thoughts, requests for help, or solutions to other people's problems, to the forum (one substantial forum post =1%, therefore you need at least 15 substantial forum posts to get all the marks. Post more if you are unsure)."

However, assessment is normally performed through a combination of different means. The AR course at the Johns Hopkins Whiting school and Engineering, has the following distribution:

- Assignments: 30%
- Projects: 30%
- Final Exam: 30%
- Class participation: 5%
- Mock-up Exam Submission: 5%

Figure 4 below presents how often different types of assessment methods are used in the selected courses. Only 16 out of 19 courses mention their assessment methods in the course descriptions.

The most commonly used assessment methods in AR courses are project and exam, but also some universities use different assessment means such as peer ranking.

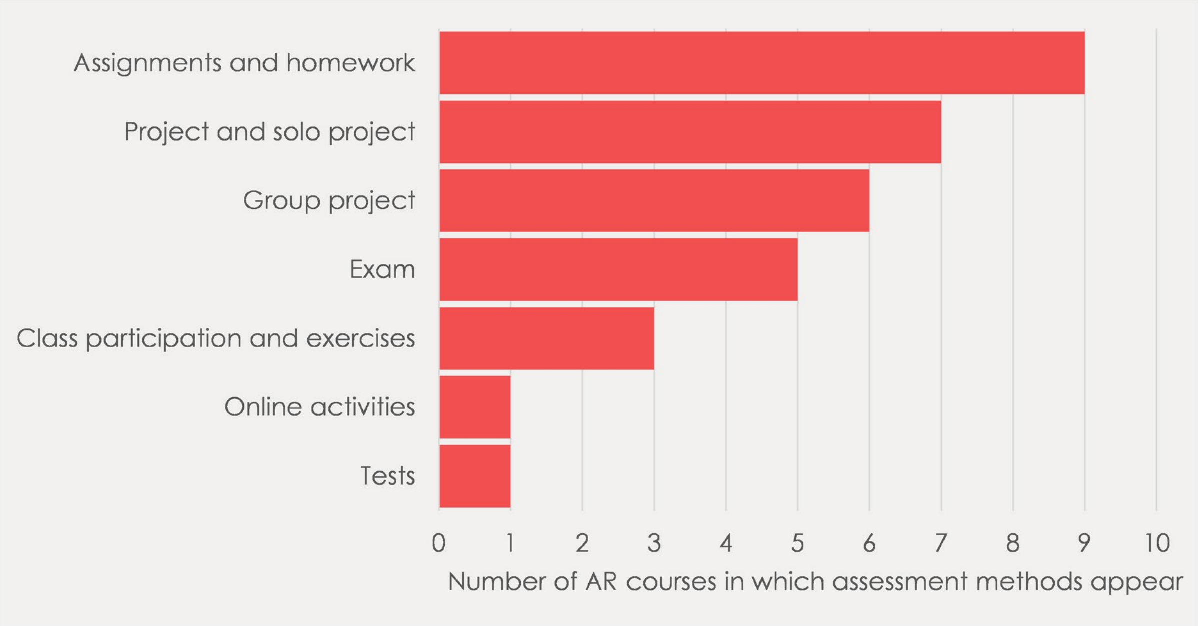


Figure 4.Different Types of Assessment

Assessments analysis indicates that almost all AR course focuses on the individual, group or unspecified type of project work as the main assessment method. The course project is a key parameter for assessing the knowledge and skills of students, which is common for applied subjects. Even though project work is necessary for such practical subjects, many courses selected for the analysis lack diversity of interaction types.

3 Summary

We selected 19 AR and AR/VR courses taught at 15 universities from lists of top 500 universities, using three different ranking (THE, QS, ARWU). The analysis of the selected courses indicates that there are no common teaching practices in the field of AR. The learning outcomes, course objectives and assessment methods are not consistent.

Approximately an equal number of courses are taught as part of programmes in Computer Science and programmes in Media. The former focus on the low-level programming of AR, while the latter on using existing libraries and building AR apps.

Part II. Future Labour Market Needs in the Field of AR

According to Statista[48], the market size for Mixed and Augmented Reality was estimated at a volume of $6.1 billion in 2016 and is expected to reach $209.2 billion by 2022. Predictions state that more than one billion users globally will create AR content at least once in 2018. Tens of thousands of apps incorporating AR capability will soon launch. 24% of all companies expect to make a substantial investment into AR technologies over the next few years to 2020[49]. AR capabilities are expected to become a key differentiating factor for apps, operating systems, and smartphones[50]. A market growing at such pace requires tens of thousands of AR specialists, a substantial increase from the current number of skilled AR professionals available today.

Developers, software designers, 3D artists, software architects and engineers, system validation engineers, project managers, marketing specialists, sales and distribution – each AR developer team has different specialist roles to fill.

Finding a university course or school that is teaching relevant AR development skills currently poses a significant challenge. Students interested in a career in AR usually are advised to choose a technical degree such as engineering or design, to later learn AR specific skills in independent study or in the workplace already.

Educational offers for AR are falling behind market demand and fail to produce the graduate numbers required. To fill this skills gap and meet demands, universities need to upgrade their curricula and include the courses needed to educate future AR experts.

But what are these skills exactly? With the survey presented in this part of the report, we intend to shed light on what are the essential (and optional) skills needed for AR developers to be successful and competitive in this fast-growing market.

In this part of the report, we elaborate further the survey objectives, methodology of data collection, and findings. We conclude with a summary of which are the essential skills in demand in the AR industry with prospective employers. The findings of this report can be used as guideline for educational institutions wishing to create a curriculum in AR.

Industry has a vested interest in ensuring university-level teaching programs are tailored to its needs, expecting the graduates hired to be ready to be productive without further specialist training. This short-term demand interest in productivity is in perpetual conflict with the long-term academic interest to secure long-term employability as well as innovation capacity looking beyond immediate applicability. A successful unit of study or even whole programme finds the right balance between building long-term capacity and ensuring short-term productivity.

In this part of the report we present results of a survey looking into expectations of companies that have or plan to have AR-competent employees.

The market study includes identifying and surveying companies working with AR (both developers and users) and surveying major European job portals to find skill requirements that the employers have for AR (including comparison data in other industrialised nations).

We recommend taking into consideration the industry point of view, especially when defining the expected learning outcomes, required competencies, and skills for improved employment intelligence.

[48] Statista (2018) https://www.statista.com/statistics/591181/global-augmented-virtual-reality-market-size/
[49] PwC (2017) https://www.pwc.com/us/en/advisory-services/digital-iq/assets/pwc-digital-iq-report.pdf
[50] Deloitte (2018) https://www.deloitte.co.uk/tmtpredictions/predictions/augmented-reality/

4 Methodology

The survey instrument aimed to identify the expectations of essential skills of AR developers that are required by organisations. This was a unique opportunity to investigate the insights and opinions of professionals.

The survey is designed for organisations that recruit or plan to recruit AR specialists – software or hardware developers, content designers, managers, etc. We are especially interested in the professional opinions of those who define what skills newly recruited AR developers need. The results of this study will be used to inform a process of designing and implementing a new course study in AR, filling the gap in the educational market.

4.1. Identification of Relevant Job Announcements

In order to identify what skills the industry requires from AR developers, we used the following methodology. We started by collecting job announcement texts from several major national and international online job portals, which included:

- indeed.com
- monster.com
- jobs.ac.uk
- jobisjob
- jobleads
- experteer
- Jobrapido
- Xing
- Jobbnorge
- Finn.no

We also searched for job announcements on social media platforms, such as Twitter, Facebook and LinkedIn.

4.2. Key Words

On all platforms, we used the key phrase "augmented reality". This phrase was translated to local European languages, but in most cases, it did not return additional results.

4.3. Data Collection

Searching for Relevant Job Announcements and Extracting Skill Lists

It is difficult to give the exact number of job announcements that were collected for the study, as some of them were posted on multiple job portals. However, the number of search results can give an estimation. For example, from jobisjob we have 394 job offers on 28.11.2017 for a query containing "augmented reality". Jobrapido revealed 310 job offers in Germany on 28.11.2017 and a similar search in Austria 11 job offers on 1.12.2017. A search on Xing (equivalent to LinkedIn for the DACH region) gave back 71 offers.

After sorting through the irrelevant items, we received 46 job announcements. In the next step in the analysis, we extracted the lists of required skills or required qualifications from these job descriptions. Such lists of skills were present in one form or another in all the job descriptions (see examples in the section above).

Categorising Skills

Next, we complied the lists of skills from individual announcements into a single list, merging any duplication of skills into the defined categories. This process resulted in 78 skills (or categories of very closely-related skills). The number of times these skills appeared in job announcements varied greatly from 1 to 21 in the 46 analysed announcements. For example, Procedural Programming (Java, C/C++, Ruby, Python) appeared in 46% of all announcements and Generic Computer Science (CS background, full-stack) appeared in 35% of announcements. This indicates a small number of basic and universal skills that are often required.

At the same time, 22 skills appeared only in a single announcement, 18 skills appeared in two announcements, and 13 skills appeared in three announcements. This indicates a large variety of skills that are specific and rare.

Clustering Skills

At the next step, we grouped the 78 skills into the following six larger categories:

- Artistic domain and content creation (e.g., 3D Artist, 3D AR/VR Artist)
- Software development and engineering (e.g., VR/AR Solution Architect, VR/AR (Senior) Developer, Software Engineer/Architect AR/VR)
- Hardware domain (e.g., Engineer Optics)
- Management and sales (e.g., Product Manager, Project Manager, Sales Manager, Support Developer, Business Development Manager for VR/AR)
- Research & development (e.g., Researcher AR/VR, Internships, Thesis work)
- Generic domain (e.g., AR/VR Specialist)

Searching for Additional Job Announcements

The next step was to perform another round of collating AR job announcements. This time, we used three different sources:

- Websites of several AR companies
- Job portals that aggregate announcements in the region of Commonwealth of Independent States (such as Hh.ru and fl.ru)
- Additional international search portals (such as jobsmarket.com)

We used the same keywords as the additional job search portals and the same criteria for filtering irrelevant announcements out.

This step resulted in 61 additional announcements, which were used to help with the additional steps of grouping and filtering the skills.

Overview of the Selected Job Announcements

Table 12 below provides an overview of the job announcements identified on both steps of data collection, the skills extracted from them and how often these skills appeared in the job announcements.

It should be noted that the number of job announcements selected for analysis from each country does not represent the number of jobs available in these countries.

Table 12. Job announcements by country

Country	Number of vacancies	Number of companies	Primary skills (in parentheses - number of mentions)
United Kingdom	33	23	▪ Augmented reality (6) ▪ Hardware and Hardware-related Skills (1) ▪ Computer vision skills (6) ▪ Computer Graphics skills (16) ▪ Advanced Computing skills (12) ▪ Specific Programming/Markup Language Skills (13) ▪ Strong interest in AR-filed, no pre-requirements (2) ▪ Project management skills (5) ▪ HCI Skills (2) ▪ Data Analysis and AI Skills (4) ▪ Platform-specific Development Skills (12) ▪ Audio Engineering Skills (1)
United States	16	12	▪ Augmented reality (3) ▪ Hardware and Hardware-related Skills (1) ▪ Computer vision skills (1) ▪ Computer Graphics skills (4) ▪ Advanced Computing skills (2) ▪ Specific Programming/Markup Language Skills (2) ▪ Project management skills (1) ▪ Data Analysis and AI Skills (2) ▪ Platform-specific Development Skills (4) ▪ HCI Skills (2)
Norway	6	4	▪ Augmented reality (1) ▪ Specific Programming/Markup Language Skills (5) ▪ Advanced Computing Skills (3) ▪ Platform-specific Development Skills (1) ▪ Computer Graphics Skills (1)
Germany	5	4	▪ Hardware and Hardware-related Skills (2) ▪ Advanced Computing Skills (3) ▪ Platform-specific Development Skills (1) ▪ Specific Programming/Markup Language Skills (2)
France	1	1	▪ Advanced Computing Skills (1)
Singapore	1	1	▪ HCI Skills (1) ▪ Strong interest in AR-filed, no pre-requirements (1)
Common wealth of Independ ent States	43	24	▪ Augmented reality (9) ▪ Computer Graphics skills (17) ▪ Advanced Computing skills (1) ▪ Specific Programming/Markup Language Skills (18) ▪ Strong interest in AR-filed, no pre-requirements (1) ▪ Data Analysis and AI Skills (1) ▪ Platform-specific Development Skills (15)

Example of an AR Job Announcement 1

Senior Software Development Engineer - Vuforia Augmented Reality

- Company name [hidden]
- Location: Cambridge, United Kingdom
- Job posted: 2017

Join Vuforia's development team in Cambridge, UK to contribute to the development of cutting-edge mobile augmented reality software. Interact closely with computer vision engineers, software developers and test engineers in a world-class AR team.

Go to www.youtube.com/user/vuforia to see Vuforia features in action.

Responsibilities:

This role covers all aspects of software development for the industry leading cross-platform mobile Augmented Reality SDK. With a strong computing or mathematical background, you will become part of the team developing the latest computer vision technologies on a range of mobile and head-worn devices.

As part of Vuforia's OEM and Platforms Team, your responsibilities will include:

- Design, development and optimisation of the Vuforia library and application code
- Creating and maintaining the platform abstractions that allow Vuforia to run efficiently on all the major mobile operating systems
- Adapting Vuforia for special hardware, for example for see-through eyewear display devices, and overcoming the technical challenges presented by these
- Enabling Vuforia to seamlessly take advantage of platform-provided computer vision components on capable devices (ARKit, ARCore, Windows Mixed Reality).

Essential skills for the role:

- Expert modern C++ knowledge and strong object-oriented development skills
- Experience developing for one or more mobile operating systems such as Android, iOS or UWP
- One or more additional relevant language (C#, Objective-C, Java, Swift etc)
- Able to design, implement and debug efficient, robust, cross-platform multithreaded code for performance critical applications
- Code profiling, tuning and optimisation
- Knowledge of 3D graphics programming, e.g. OpenGL, DirectX or Metal
- Scripting languages such as bash, Python or Lua

Desirable skills and experience:

- Agile development and continuous integration
- Capable of working at the level of machine instructions when necessary
- Hardware accelerated computation (e.g. Neon, SSE, GPGPU, DSP…)
- Good understanding of 3D geometry and matrix mathematics
- Some use of or exposure to the Unity 3D game engine
- Prior knowledge of Augmented Reality, Virtual Reality or Computer Vision

Education:

- B.S., M.S. or PhD (Computer Science, Information Science or Mathematics)

What we offer?

- Work in a world-class development team in a dynamic environment
- Contribute to leading edge technology used by millions of people
- The ability to influence and make a significant impact on our products
- A fascinating, flexible, and fun work environment

Example of an AR Job Announcement 2

Computer Vision Research Engineer - Augmented Reality

- Company name: [hidden]
- Location: Mountain View, California
- Job posted: 2017

[Company] offers the unique combination of the visibility and flexibility of a startup with the stability of a mature company. We aim to attract top engineers and researchers with the skills and passion to drive revolutionary transformation of the global transportation industry.

As a young team, our desire is to build and maintain a working environment that engenders free flow of ideas and sets our employees up for strong personal growth and career development.

We are looking for experienced computer vision research engineers in our Mountain View office to develop algorithms and systems for [Company] projects on augmented reality. The goal is to apply cutting-edge algorithms and technologies on cars to redefine the way we experience and interact with cars. We are interested talents in all relevant areas: machine learning, computer vision, image processing and computer graphics etc. We are thrilled to have top-notch talents joining us to shape the future of cars and deliver revolutionarily exciting experiences to millions of [Company] customers.

Responsibilities:

- Research and develop algorithms and systems for augmented reality applications. Used to reimagine the way people interact with the surrounding world and improve their car driving and riding experience.
- Collaborate with other engineers and teams to deliver prototype and/or production solutions.
- Contribute to [Company] intellectual property portfolio through patient filing.
- Track latest advancements and maintain a current understanding of related research areas.

Qualifications:

- Ph.D. (preferred) or master's degree in Computer Science, Computer Engineering, Electrical Engineering or related programs.

Expertise in one or more following areas: machine learning, computer vision, image processing, computer graphics. Hands-on experience and deep understanding in one or more of the following will be preferred:

- Machine learning, esp. deep learning, applied to visual recognition or understanding, e.g. object recognition and localisation, semantic segmentation, scene understanding, etc.
- 3D computer vision: structure from motion (SfM), stereo vision, visual SLAM, Visual (Inertial) Odometry
- Large-scale content-based image or video retrieval.
- Single or multi-target visual tracking.
- Strong publication record and/or proven track record of delivering solid technologies or products in above areas is a large plus.
- Solid knowledge in fundamental algorithms and data structures.
- Programming proficiency in C++ and/or Python.
- One or more of the following skills will be a bonus:
- GPU programming: CUDA, OpenCL, OpenGL etc.
- Infrastructure of big data, high performance computing and/or distributed system.
- Programming mobile or embedded devices, including code performance optimisation.
- Development of web apps and/or micro-services.

- Passion for R&D and technical excellence, strong problem analysis and solving skills.
- Effective verbal and written communication and a spirit of collaboration in a rapidly growing team.

Grouping and Filtering Skills

Next, we detailed the skills in the groups and split some of them into more specific categories. This process resulted in 13 categories of skills:

- AR/VR Development Skills
- Data Analysis and AI Skills
- Platform-specific Development Skills
- Computer Graphics Low Level Skills
- 3D Modelling Skills
- Specific Programming/Markup Language Skills
- Audio Engineering Skills
- Design/artistic Skills
- Interaction Design Skills
- Hardware and Hardware-related Skills
- Computer vision skills
- Generic Software Development Skills
- Project management skills

In order to narrow down the scope of the study, we then removed the following three categories of skills:

- Generic software development skills category was defined as a set of prerequisite skills for an AR specialist
- Design/artistic skill category was removed from the core AR skills, the job announcements for AR designers were very isolated
- Project management skill category was considered to contain skills that are the same for most of IT specialists

4.4. Top 10 skills for AR Specialists

As a result of the analysis of the selected job announcements, we outlined the following key skills for AR developer specialists (in random order):

- AR/VR Development Skills
- Platform-specific Development Skills
- Specific Programming/Markup Language Skills
- Advanced Computing Skills
- Computer Vision skills
- Computer Graphics Skills
- Data Analysis and AI Skills
- Audio Engineering Skills
- HCI Skills
- Hardware and Hardware-related Skills

4.5. Survey Design

Objective and Target Group

The list of the top 10 skills for AR specialists identified via the analysis of job announcements, was further used as the main component of our survey "Essential skills for Augmented Reality developers in Industry". The objective of running the survey was to test how important are these top 10 skills for the industry.

The survey was targeted at different AR professionals, especially those who are taking decisions about hiring developers, and therefore aware of the required skills.

We asked the respondents to rank the top 10 skills according to whether they consider them to be essential for AR developers.

Design Considerations

The critical factors used in the process of constructing the survey were:

- Questionnaire clarity (minimalising ambiguousness, understandable language, avoiding confusingly phrased questions, eliminating double-barrelled questions)
- Comprehensiveness (sufficient questions and answers to cover reasonably complete range of skills)
- Acceptability (no excessive length)

We aimed to create a questionnaire that could be filled in within 7 minutes, but the final version required 15 minutes.

Structure of the Survey Design

The questionnaire consisted of three sections that were addressed to the respondent:

- Contextual information about the organisation the respondent belongs to
- Essential skills for AR specialists
- An option for the respondent to provide contact information

In total, the final questionnaire consisted of questions with sub-parts that addressed 76 data points. The survey parts are described as follows.

Survey Section 1: Contextual Information

In this section of the survey, we asked for information to help us correctly categorise and analyse the results. The contextual questions in section 1 of the survey included:

- Size of organisation
- Country
- Position type of the person filling in the survey
- Industry group or type of public organisation

In the question about the position type, we provided the following options:

- Professional
- Technicians and associate professionals
- Other (Academic)
- Managers
- Clerical support workers

In the question about the Industry group or type of public organisation, we provided the following options:

- Software & Services
- Technology Hardware & Equipment
- Automobiles & Components
- Architecture, Construction, and Building
- Commercial & Professional Services
- Consumer Services
- Energy
- Health Care Equipment & Services
- Materials
- Media
- Pharmaceuticals, Biotechnology & Life Sciences
- Real Estate
- Retailing
- Semiconductors & Semiconductor Equipment
- Telecommunication Services
- Transportation & Logistics
- Education and Research
- Health Care
- Public Administration & Government
- Police
- Other

We also asked two questions about any personal experience in recruiting and hiring AR specialists with yes-no options:

- Have you been actively involved or plan to be involved in the recruitment of an AR specialist?
- Does your organisation have AR specialists or does it consider hiring AR specialists?

Survey Section 2: Essential Skills for AR Specialists

In this section of the survey, we asked professional opinion on the 10 essential skills for AR specialists. Each key skill group (Table 13) was rated on a Likert scale from 1 to 5, where 1 is strongly disagree, 2 is disagree, 3 is neutral, 4 is agree and 5 is strongly agree.

After rating key skills, the respondents were invited to rate more detailed sub-skills in each category on the same scale from 1 to 5 (Table 13, last column).

Table 13. Skills groups and specific skills rated by the respondents

No	Skill group	Specific skills
1	AR/VR Development Skills	▪ AR SDKs (ARcore, ARkit, HoloToolkit, ARtoolkit, etc.) ▪ VR SDKs (PSVR, Oculus, OpenVR, WebVR, etc.) ▪ Unity ▪ Unreal Engine ▪ AR/VR game development experience
2	Platform-specific Development Skills	▪ iOS (Objective C, Swift, XCode, etc.) ▪ Android (Java, Kotlin, Android Studio, etc.) ▪ Linux, Windows, MacOS X ▪ Multi-Platform Development, Cross-Device Development, Mobile ▪ Real time embedded software development / embedded development environments ▪ Cloud Services (Azure, AWS, Google App Engine, etc.) ▪ Scalability (Modules, Microservices, etc.)
3	Specific Programming / Markup Language Skills	▪ .NET (C#, Mono) ▪ Procedural Programming (Java, C/C++, Ruby, Python) ▪ JavaScript Frameworks (React, Angular, Vue) ▪ Web Front-ends (HTML5, CSS3, ES6)
4	Advanced Computing Skills	▪ GPU programming for advanced shading (such as NPR, global illumination, shadow, particles) ▪ Hardware accelerated computation (such as Neon, SSE, GPGPU, DSP…) ▪ CPU and GPU optimisation ▪ Graphic APIs (OpenGL, OpenGL ES, Vulkan or DirectX) ▪ Compute APIs (CUDA, OpenCL, etc.) ▪ Software optimisation and instrumentation techniques ▪ Multi-threaded programming
5	Computer vision skills	▪ Computer vision, image analysis, image processing, OpenCV ▪ Object detection and recognition, 3D sensing, tracking ▪ Depth Sensing
6	Computer Graphics Skills	▪ Generic CG & VFX (Texturing, Animation, 3D modelling, lighting & rendering) ▪ 3D modelling (3ds Max, Maya, Modo, Blender, etc.) ▪ Interactive 3D graphics design ▪ Rendering (Vray, Corona, Octane, etc.) ▪ CAD tools (Autodesk CAD tools, Solidworks, Catia, experience with Geometric Dimensioning and Tolerancing, etc.) ▪ 3D math and Math for graphics
7	Data Analysis and AI Skills	▪ Data analysis and manipulation (Matlab, R, SPSS, etc.) ▪ Machine learning, deep learning libraries (TensorFlow, Torch, Caffe, etc.) ▪ Artificial Intelligence ▪ Big data and data mining ▪ Algorithms
8	Audio Engineering Skills	▪ Spatial Audio (Audio DSP, FMOD) ▪ Sound design, Composition and Production (sound generation, mixing, etc.)

9	HCI Skills	▪ Basic artistic/design skills (hand sketching, illustration, etc.) ▪ Design tools (Adobe Creative Suite, InVision, Sketch, whiteboards, paper sketches, Adobe XD or Illustrator) ▪ User-centred design (Accessibility and Universal Design, UX design, Usability, etc.) ▪ User interface design ▪ Gesture interaction ▪ Eye Gaze tracking/interaction ▪ Speech interaction
10	Hardware and Hardware-related Skills	▪ AR Smart Glasses (HoloLens, Epson BT300, Magic Leap One, Meta One, ODG R-9, DAQRI Smart Glasses, etc.) ▪ AR projection solutions ▪ Optical design (Optical design software, optics, and frames) ▪ Maker skills (3D printing, arduino, microcomputers) ▪ Robots ▪ Internet of Things ▪ Sensors ▪ Wearables ▪ Signal processing (for context sensing or for sensor fusion) ▪ Drivers, Hardware Abstraction Layer (HAL)

Survey Section 3: Optional Contact Information

Respondents could provide their email if they wished to get a copy of the survey results and to stay up to date with the progress of the project.

Online Questionnaire

We implemented the survey as an online questionnaire because of numerous advantages: convenience, rapid data collection, cost-effectiveness, ample time, ease of follow-up, confidentiality and security and specialised target group[51] [52]. The software tool that was used was the LimeSurvey platform. The survey is still available online at http://codereality.net/survey/.

An email with an invitation to participate in the survey with an embedded URL link to the survey web page was sent to over 200 people selected from the professional networks of AR-FOR-EU consortium, including contacts collected in previous work. In addition, it was also distributed on social media.

[51] L. M. Rea and R. A. Parker (2005) 'Designing and Conducting Survey Research: A Comprehensive Guide'
[52] D. A. De Vaus (2014) 'Surveys in social research'

5 Data Analysis Approach

The descriptive statistics were used to analyse the data. The mean was used as a measure of central tendency, although the data is ordinal in nature, because it provided more information than the median[53]. The data were analysed using IBM SPSS Software Version 25.

Spearman's correlations statistics were used to discover the associations between contextual information, between the contextual information and skills, and between skills. Spearman's rank correlation coefficient is a nonparametric measure of rank correlation (statistical dependence between the rankings of two variables). It assesses how well the relationship between two variables can be described using a monotonic function.

Contingency tables and Fisher's exact test were used to discover different attitudes in studied groups. The Fisher's test was used to determine whether there is a significant difference between the expected frequencies and the observed frequencies in one or more categories.

6 Results and Analysis

We have been collecting the results from 12.03.2018 until 28.05.2018. We have received 381 responses, out of these, 76 responses were complete (Table 14). The incomplete responses were unsubmitted questionnaires, where participants had typically browsed past the context section to see what the questionnaire contained.

Table 14. Numbers of responses

Type of responses	Number of responses
Full responses	76
Incomplete responses	305
Total responses	381

6.1. Contextual Information

Seventy-six participants answered the survey in full. They represent 24 countries in total. Out of them, the responses were submitted from 18 European countries as well as Australia, Canada, Malaysia, Russian Federation, Taiwan and United States (Fig. 5).

[53] L. M. Rea and R. A. Parker (2005) 'Designing and Conducting Survey Research: A Comprehensive Guide'

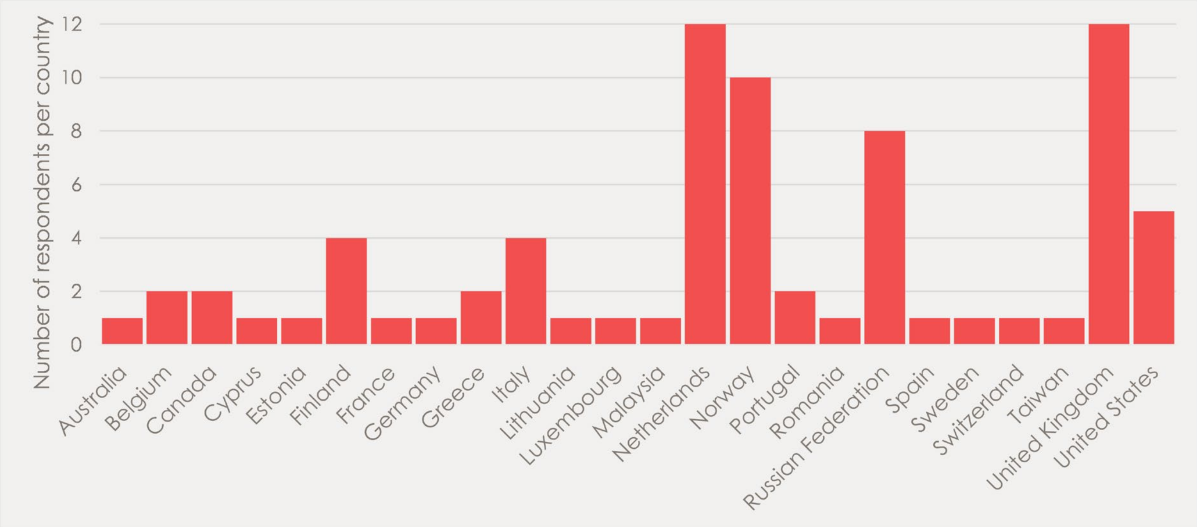
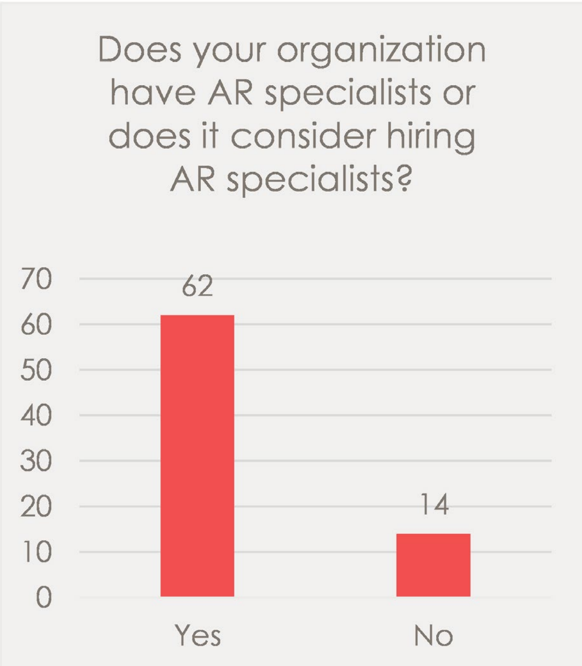


Figure 5.Survey respondents by country

The figure below shows that 62 out of 76 respondents (82%) stated that their organisation has AR specialists, or it considers hiring AR specialists (Fig. 6, left).

It also shows that 41 out of 76 respondents (55%) have been actively involved in the process of recruitment of AR specialists (Fig. 6, right).



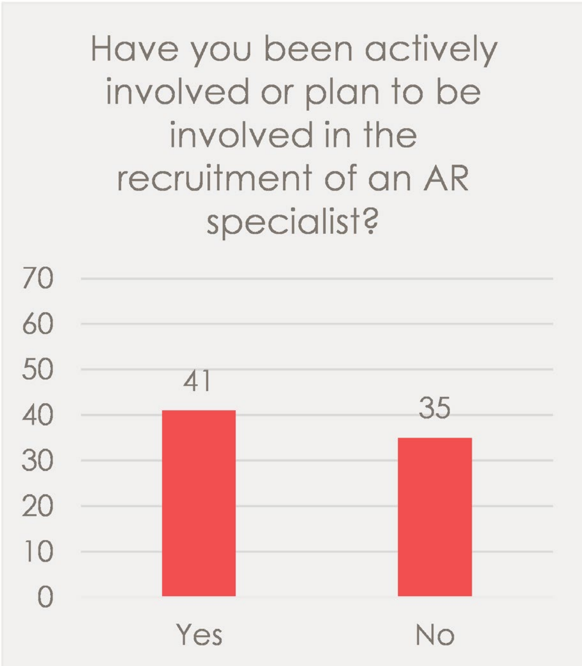


Figure 6.Organisational and personal experience in recruiting and hiring AR specialists

In figure 7 below, we can see that most respondents (44%) work in large organisations (250 or more employees), 41% respondents work in medium size organisations (between 10 to 249 employees), and 20 % work in small organisations (Fig. 7).

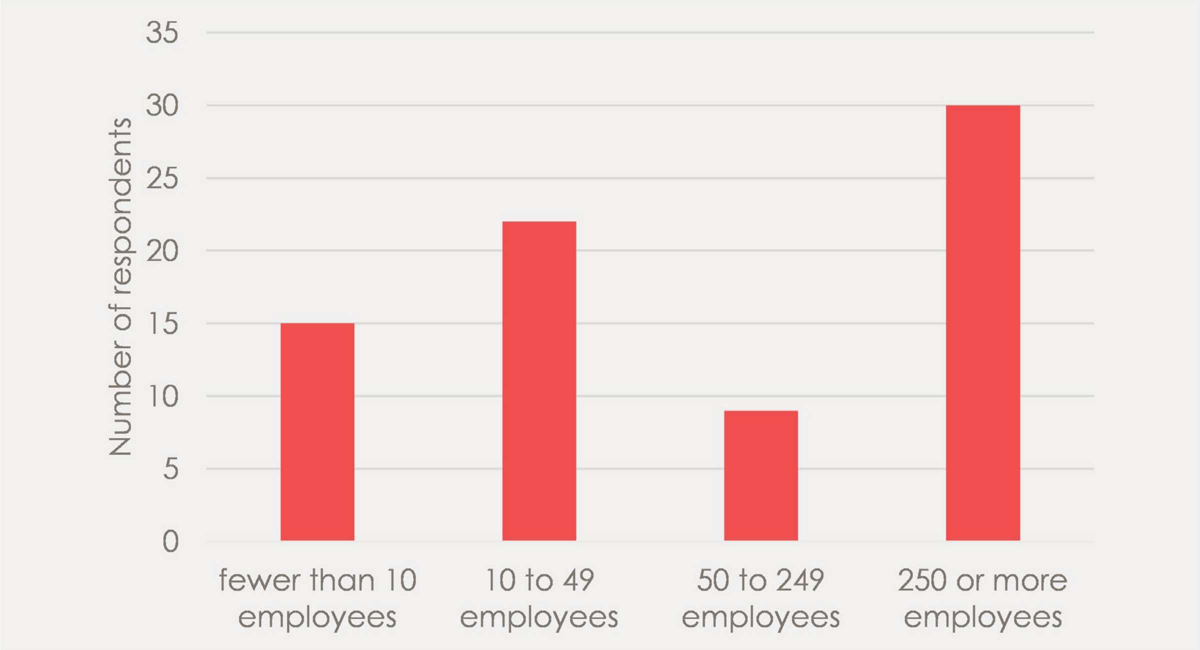


Figure 7.Size of the organisation

The professions of participants of the survey and size of their workplaces can be seen on Figure 8 below. They are working as professionals (47%), managers (32%), technicians and researchers (both groups 9%). In the category 'Other', seven respondents were academics and two were professionals.

The larger the organisation, the more likely they are to hire an AR specialist.

Figure 8.Position in the organisation

Most of the respondents represent Education and Research (47). Another large group works in software and services (32). Smaller, but still noticeable group works in the domain of hardware and equipment (14). The details are presented on Figure 9 below.

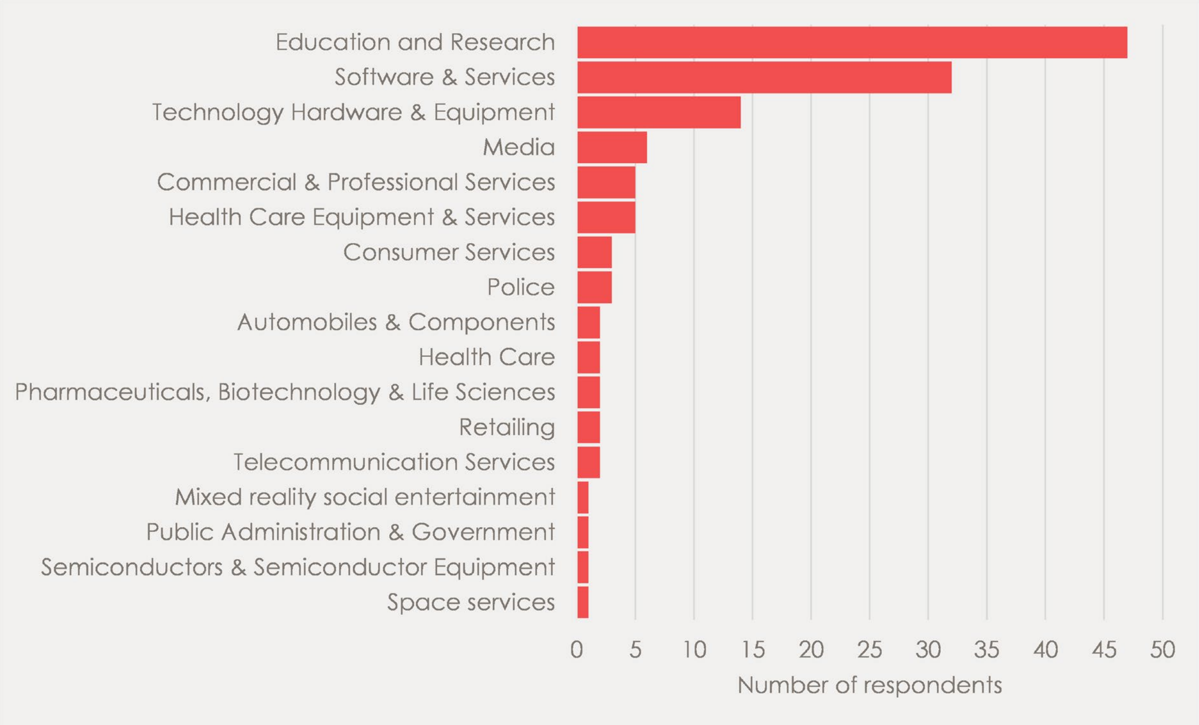


Figure 9.Industry group or type of your public organisation

6.2. Essential Skills for AR Specialists

The reader will find a detailed description of all the 10 main groups of AR skills that were studied below. For each skill we asked:

'We are going to have increased demand for this skills in our organisation over the next 3-5 years' and we requested the participant to mark if they agree or disagree with each statement on 5 point scale where 1 strongly disagree, 2 disagree, 3 neutral, 4 agree and 5 – strongly agree.

For each category of the essential skills for AR specialists, basic descriptive statistics were calculated (mean and standard deviation). They are presented in the tables in each section. That allowed us to compare which skills were rated as more important.

Afterwards we investigated more deeply which skills were rated as important by focusing on the answers 'agree' and 'strongly agree' from participants in the questionnaire. The frequencies of those answers were presented on graphs in each section. That allowed us to determine which skills are most important for professionals working in the AR domain.

AR/VR Development Skills

We started the inquiry from asking about the AR/VR development skills. We decided to combine AR and VR because we wanted to know if there is a focus on AR or it is perceived as a part of mixed reality.

In the sub categories, we asked about:

- AR software development kits (SDKs) (such as, ARcore, ARkit, Vuforia, HoloToolkit, ARtoolkit, etc.)
- VR software development kits (such as, PSVR, Oculus, OpenVR, WebVR, etc.)
- The cross-platform game engine developed by Unity Technologies
- The Unreal game engine by Epic Games
- Generic AR/VR game development experience

Table 15. AR/VR development skills

Skill	N	Mean	Std. dev.
AR/VR Development Skills	76	4.45	0.870
AR SDKs (ARcore, ARkit, Vuforia, HoloToolkit, ARtoolkit, etc.)	71	4.48	0.808
VR SDKs (PSVR, Oculus, OpenVR, WebVR, etc.)	71	4.06	0.998
Unity dev. experience	69	4.39	0.878
Unreal Engine dev. experience	66	3.48	1.085
AR/VR game dev. experience	67	4.03	1.044

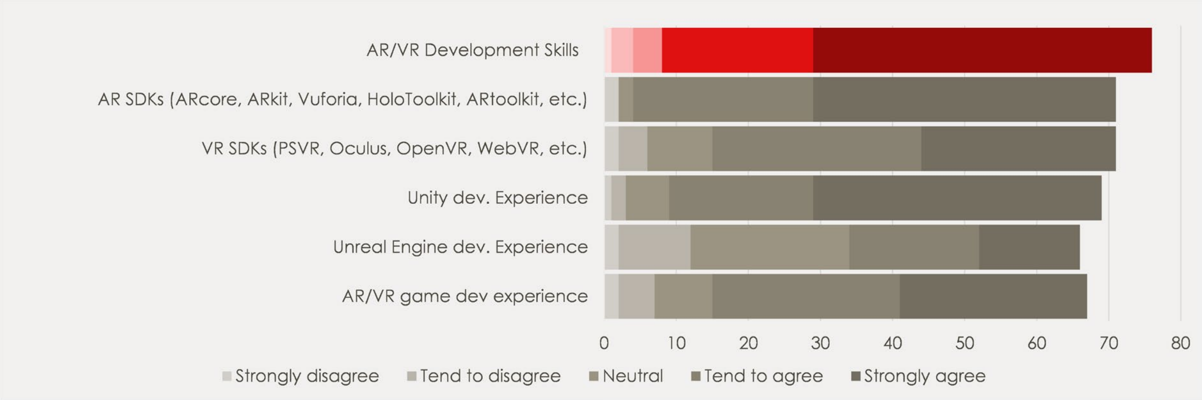


Figure 10. AR/VR Development Skills

From Table 15, we can see that respondents perceive AR software development kits as very important with the mean value 4.48, even more important that generally AR development skills with the mean 4.45. The second very important skill was knowledge of Unity with a mean of 4.39.

From Figure 10 above, we can see that skills in AR software development kits were naturally valued as more important than VR software development kits. That is in line with our expectations, as the focus of the study is on AR. Unity is seen as more important than Unreal. Unity is one of most widespread game engines. It provides advanced 3D graphics rendering and exports to mobile devices for free[54]. Unreal was ranked much lower than any other sub-category.

[54] E. Christopoulou and S. Xinogalos (2017) 'Overview and Comparative Analysis of Game Engines for Desktop and Mobile Devices'

Platform-specific Development Skills

In the second question, we asked the opinions about the skills needed in different platforms. With the rapid development of mobile technology, it was important for us to know if it affects the market of specialists.

The subcategories were as follows:

- iOS, a mobile operating system created and developed by Apple exclusively for its hardware (like Objective C, Swift, XCode, etc.)
- Android, a mobile operating system developed by Google, based on a modified version of the Linux kernel and other open source software and designed primarily for touchscreen mobile devices (Java, Kotlin, Android Studio, etc.)
- Desktop PC platforms such as Linux, Windows, Mac OSX
- Multi-platform development (development across devices and mobile)
- Real time embedded software development / embedded development environments
- Cloud services (Azure, AWS, Google App Engine, etc.)
- Scalability (Modules, Microservices, etc.)

Table 16. Platform-specific development Skills

Skills	N	Mean	Std. dev.
Platform-specific Development Skills	76	4.28	0.776
Scalability (Modules, Microservices, etc.)	65	3.74	1.079
Cloud Services (Azure, AWS, Google App Engine, etc.)	63	4.10	0.962
Real time embedded software dev. / embedded dev. envs.	62	3.79	1.073
Multi-platform development, cross-device development, mobile	65	4.42	0.900
Linux, Windows, MacOS X	63	4.00	0.803
Android (Java, Kotlin, Android Studio, etc.)	63	4.05	1.007
iOS (Objective C, Swift, XCode, etc.)	64	3.75	1.113

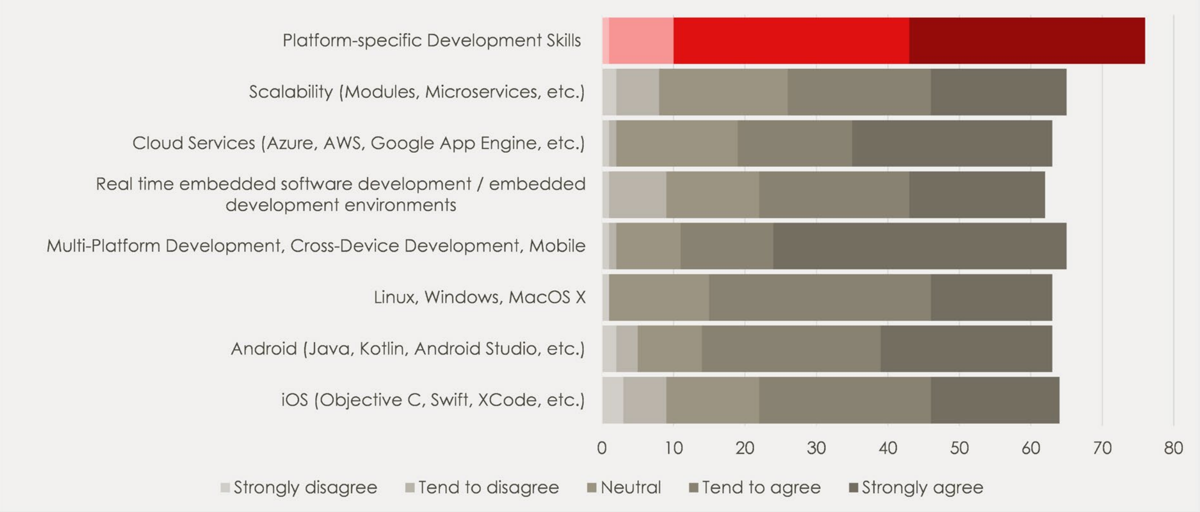


Figure 11. Platform-specific Development Skills

In table 16, we can see that the highest mean (4.42) result was for multi-platform development skills, cross-device development and mobile. The result was even higher than the main skill platform-specific development with the mean 4.28. We can see very similar values from results in these three categories: cloud services (mean 4.1), Android (mean 4.05) and Linux, Windows, MacOS (mean 4.0).

From graph 11 we see that multi-platform development skills were ranked as the most important platform-specific skills. This skill is vital as it enables code to be written once and employed across multiple platforms – Android, iOS, or Windows. Using cross platform app development ensures that the overall look of the application can be maintained across all platforms since the same set of codes are being utilised. The same category mentioned mobile technology which is becoming increasingly popular since the smartphone devices now have the necessary capabilities to access locational data and overlay information onto the user's surroundings[55].

The respondents have chosen Android as more important than iOS. Both ecosystems are populated by hundreds of thousands of app developers that offer a wide variety of specialised software applications to smartphone users, the difference between them is largely characterised by Apple's closed model and Google's open model[56].

Respondents also indicated that developing for desktop operating systems like Linux, Windows and MacOS X are important skills.

Specific Programming / Markup Language Skills

In the third question, we investigated programming and language skills. It is the essential ability for any AR developer, therefore we need to investigate which languages are the most useful. We proposed the following set of types of languages:

- Web front-ends (such as HTML5, CSS3, ES6)
- JavaScript frameworks (such as React, Angular, Vue)
- Procedural programming that specifies a series of well-structured steps and procedures within its programming context to compose a program (Java, C/C++, Ruby, Python)
- .NET, a software framework developed by Microsoft that provides language interoperability across several programming languages (C#, Mono)

Table 17. Specific Programming / Markup Language Skills

	N	Mean	Std. dev.
Programming / Markup Language	76	4.16	0.880
Web Front-ends (HTML5, CSS3, ES6)	62	4.08	0.980
JavaScript Frameworks (React, Angular, Vue)	61	4.03	0.983
Procedural Programming (Java, C/C++, Ruby, Python)	62	4.16	0.891
.NET (C#, Mono)	63	3.95	1.156

[55] T. Liao (2018) 'Mobile versus headworn augmented reality: How visions of the future shape, contest, and stabilise an emerging technology'.
[56] R. Kapoor and S. Agarwal (2017) 'Sustaining Superior Performance in Business Ecosystems: Evidence from Application Software Developers in the iOS and Android Smartphone Ecosystems'

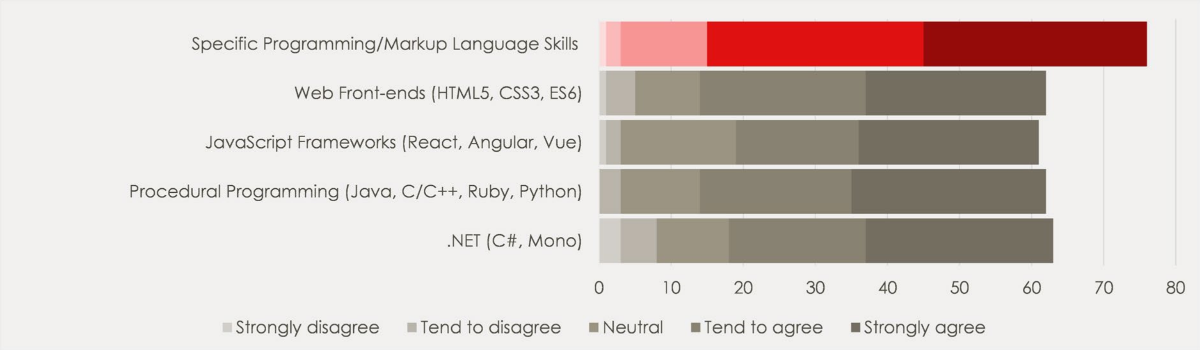


Figure 12. Specific Programming / Markup Language Skills

From table 17, we can read that the main category - programming / markup language was valued the highest (mean 4.16). From the subcategories procedural programming languages was valued as high (with the mean also 4.16).

From figure 12, we can clearly see that the biggest interest is in the main category - specific programming / markup language. From the subcategories the results look similar. Procedural programming, languages like Java, C/C++, Ruby, Python are most important for AR developers. Web front ends like HTML5, CSS3, ES6 are also seen as useful programming skills for AR specialists. HTML is the standard markup language for creating web pages and web applications. With CSS and JavaScript, they form a triad of cornerstone technologies for the World Wide Web.

Advanced Computing Skills

In the fourth question, we asked about the following advanced computing skills:

- Graphics processing unit (GPU) programming for advanced shading which is used primarily for 3D applications to creates lighting effects and transforms objects every time a 3D scene is redrawn
- Hardware accelerated computation which is the use of computer hardware to perform some functions more efficiently than is possible in software running on a more general-purpose central processing unit (CPU)
- CPU and GPU optimisation
- Graphic application programming interfaces (APIs)
- Compute APIs (CUDA, OpenCL, etc.)
- Software optimisation and instrumentation techniques
- Multi-threaded programming which is the ability of a central processing unit to execute multiple processes or threads concurrently, supported by the operating system

Table 18. Advanced Computing Skills

	N	Mean	Std. dev.
Advanced Computing	76	4.03	0.966
Multi-threaded programming	58	4.02	0.908
Software optimisation and instrumentation techniques	60	4.03	0.901
Compute APIs (CUDA, OpenCL, etc.)	58	3.9	1.087
Graphic APIs (OpenGL, OpenGL ES, Vulkan or DirectX)	60	3.92	0.979
CPU and GPU optimisation	59	3.95	1.151
Hardware accelerated computation (Neon, SSE, GPGPU, DSP)	60	3.7	1.062
GPU programming for advanced shading (NPR, global illum. etc.)	59	3.9	0.977

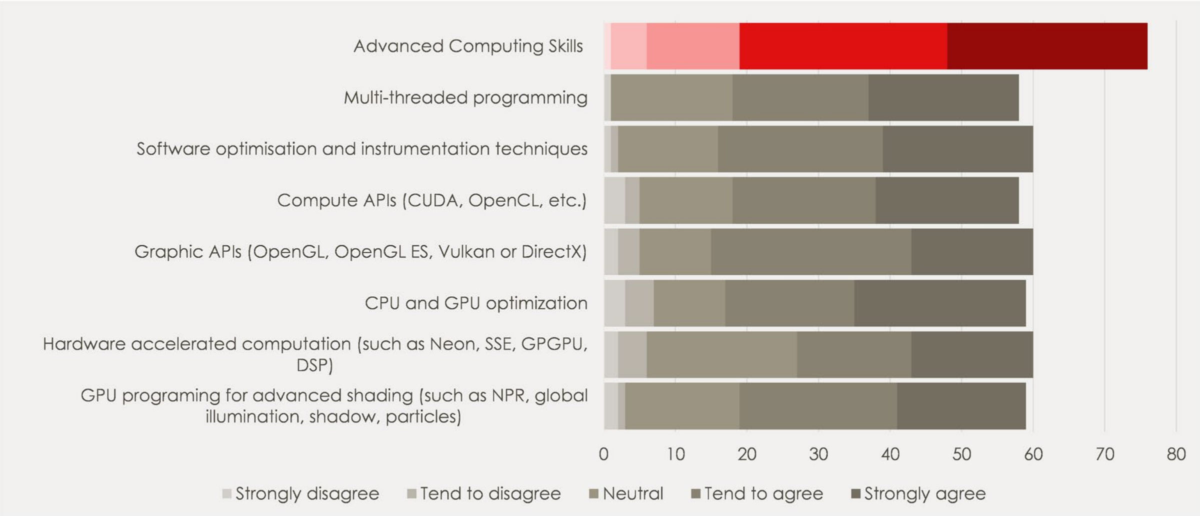


Figure 13. Advanced Computing Skills

In table 18, we can see the mean values for this category. Advanced computing skills, the main category has the highest mean (4.03). The same mean has software optimisation and instrumentation techniques along with multi-threaded programming (4.02). Similarly we can see at figure 13 that they are the most important advanced computing skills. Software optimisation is the process of modifying a software system to make it work more efficiently or use fewer resources. The importance of the software architecture optimisation techniques is rapidly growing due to the significant increase in industrial demands toward software systems with high complexity and challenging quality requirements[57].

AR specialists need to be able to deliver high quality product to ensure the AR experience. Multi-threaded programming has been used for achieving many high-performance computing goals in recent years[58]. Multi-threaded programming has many benefits that can be used in AR applications, as it allows you to take advantage of unused computing resources, which leads to faster overall execution.

Computer vision skills

In the fifth question, we asked about one of the most important elements of AR – computer vision. Computer vision is an interdisciplinary field that deals with how to gain high-level understanding from digital images or videos. We asked which elements of computer vision are the most important for AR specialists: computer vision, image analysis, image processing, OpenCV (Open Source Computer Vision - which is a library of programming functions mainly aimed at real-time computer vision); object detection and recognition, 3D sensing, tracking; and depth sensing.

Table 19. Computer vision skills

Skills	N	Mean	Std. dev.
Computer vision skills	76	4.17	0.971
Depth Sensing	64	4.16	1.057
Object detection and recognition, 3D sensing, tracking	64	4.36	0.932
Computer vision, image analysis, image processing, OpenCV	64	4.34	0.930

[57] L. Grunske and A. Aleti (2013) 'Quality optimisation of software architectures and design specifications'
[58] S. Barbhuiya and S. Ying Liang (2012) 'A multi-threaded programming strategy for parallel Weather Forecast Model using C#'

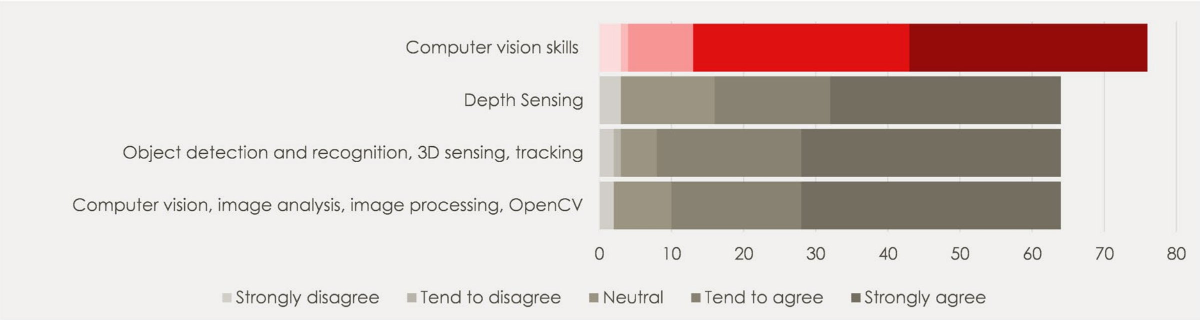


Figure 14. Computer vision skills

Object detection and recognition, 3D sensing, tracking as well as computer vision, image analysis, image processing, OpenCV are the most important computer vision skills for our respondents, with means respectively 4.36 and 4.34 (as can be seen in the table 19 and figure 14). Already Azuma indicated that image processing and computer vision are used to detect features of the environment and use them to reinforce registration[59]. The computer vision skills are especially important in order to enhance the interaction with the real world, augmented reality displays must combine computer-generated elements with real-world elements[60]. Schmalstieg and Hollerer claim that computer vision, aided by other sensors, is a key ingredient to successful reality tracking and registration[61].

Computer Graphics Skills

In the sixth question, we asked about the computer graphics skills. To create high quality user experience, AR specialists need to have these skills. We asked about the following skills:

- 3D math and math for graphics
- Computer Aided Design (CAD) tools
- Rendering (Vray, Corona, Octane, etc.)
- Interactive 3D graphics design
- 3D modelling (3ds Max, Maya, Modo, Blender, etc.)
- Generic computer graphics and visual effects (VFX)

Table 20. Computer Graphics Skills

Skills	N	Mean	Std. dev.
Computer Graphics Skills	76	4.13	0.957
3D math and Math for graphics	62	3.95	1.047
CAD tools (Autodesk CAD, Solidworks, Catia, Geometric Dimensioning, etc.)	64	3.72	1.076
Rendering (Vray, Corona, Octane, etc.)	63	3.49	1.105
Interactive 3D graphics design	65	4.17	0.945
3D modelling (3ds Max, Maya, Modo, Blender, etc.)	65	4.06	0.966
Generic CG & VFX (texturing, animation, 3D modelling, light. etc.)	64	4.09	0.904

[59] R. T. Azuma (1997) 'A survey of Augmented Reality'
[60] S. Ghasemi, M. Otsuki, P. Milgram and R. Chellali (2017) 'Use of Random Dot Patterns in Achieving X-Ray Vision for Near-Field Applications of Stereoscopic Video-Based Augmented Reality Displays'
[61] D. Schmalstieg and T. Höllerer (2016) 'Augmented Reality Principles and Practice'

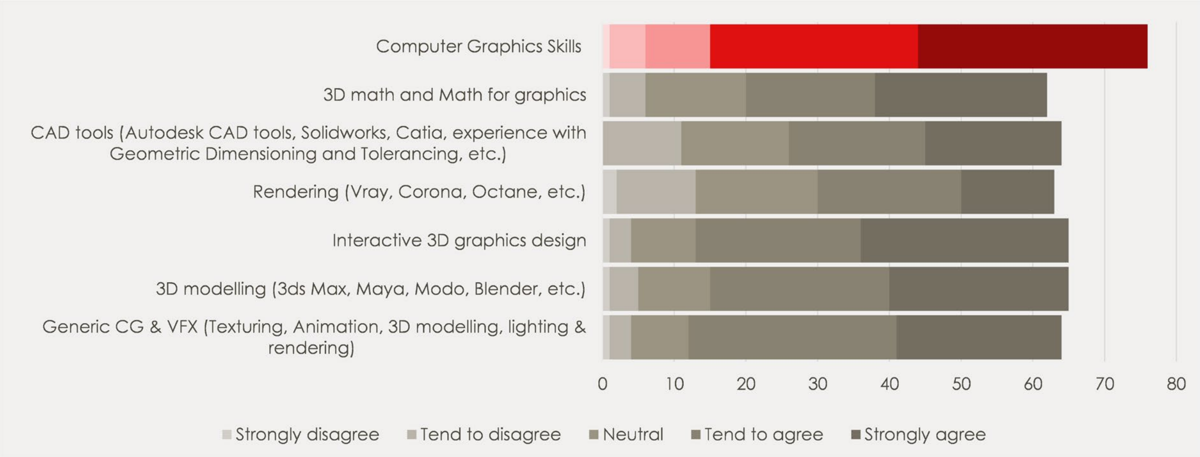


Figure 15. Computer Graphics Skills

From table 20 we see that interactive 3D graphic design (mean 4.17) is the most important skill in this category, followed by general category of computer graphics skills (mean 4.13).

From figure 15, we see that Interactive 3D graphic design, 3D modelling and Generic CG & VFX are valued the highest from the graphic skills. AR displays allow overlaying of virtual two-dimensional (2D) or three-dimensional (3D) images on the viewer's real world view. Early AR creators focused on identifying 2D fiducial markers in the AR scene, only a small amount of research has been devoted to the perception of 3D objects[62]. But the AR displays which can only superimpose 2D images on real 3D scene, cannot display the image with the same depth as real objects[63]. Only when the 3D image overlaps with the real 3D scene in viewer's eyes is the AR 3D perception achieved.

Data Analysis and AI Skills

In the seventh question, we asked about data analysis and artificial intelligence (AI) skills. For creating reliable AR experiences, a considerable amount of data needs to be used. Hence, we investigate the importance of data analysis and AI skills. We asked specifically about the following skills:

- Algorithms
- Big data and data mining
- Artificial Intelligence
- Machine learning, deep learning libraries (TensorFlow, Torch, Caffe, etc.)
- Data analysis and manipulation (Matlab, R, SPSS, etc.)

Table 21. Data Analysis and AI Skills

Skills	N	Mean	Std. dev.
Data Analysis and AI Skills	76	4.32	0.883
Algorithms	65	4.08	1.005
Big data and data mining	64	4.11	1.100
Artificial Intelligence	66	4.27	0.921
Machine learning, deep learning libs (TensorFlow, Torch, etc.)	65	4.35	0.975

[62] H. Chen et al. (2016)'3D registration based perception in augmented reality environment'
[63] H. Deng et al. (2016) 'Magnified augmented reality 3D display based on integral imaging'

Data analysis and manipulation (Matlab, R, SPSS, etc.)	65	3.91	1.155

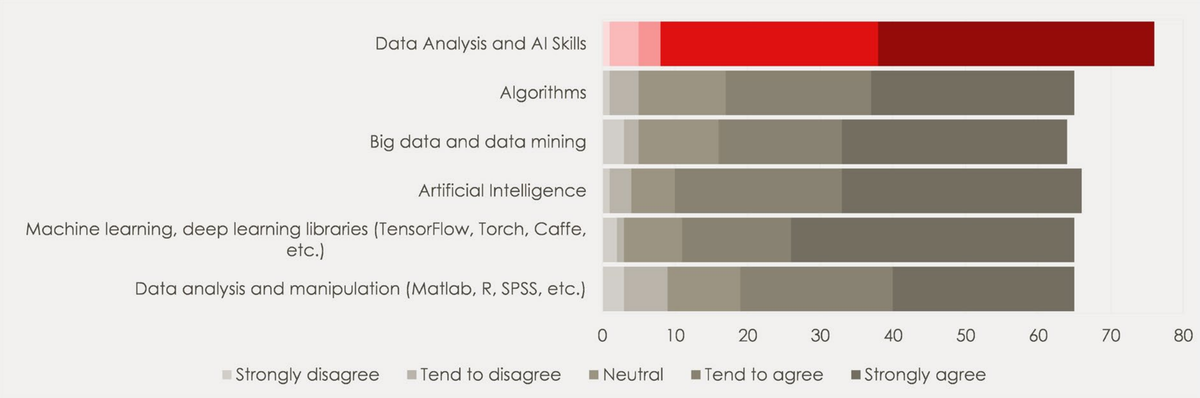


Figure 16. Data Analysis and AI Skills

From table 21 we can see that there are three most important skills: Machine learning (mean 4.35), Data Analysis and AI skills (4.32) and Artificial Intelligence (4.27).

From figure 16 we see that machine learning and artificial intelligence were ranked as the most important in this category. Machine learning gives computer systems the ability to "learn" with data, without being explicitly programmed (Fig. 16). Artificial intelligence is applied when a machine mimics "cognitive" functions that humans associate with other human minds, such as "learning" and "problem solving". Both those technologies can be used in AR applications to understand human speech, compete at higher level in strategic game systems and autonomously operate cars, etc. The combination of AR and Artificial Intelligence might open new possibilities for the development of user interfaces in the nearest future.

Audio Engineering Skills

In the eighth question, we asked about audio engineering skills. Arguably as important as visual experience are audio experiences. We asked which audio engineering skills play an important role for AR:

- Spatial audio (Audio DSP, FMOD)
- Sound design, composition and production

Table 22. Audio Engineering Skills

	N	Mean	Std. dev.
Audio Engineering Skills	76	3.3	1.096
Spatial audio (Audio DSP, FMOD)	60	3.43	1.125
Sound design, composition & prod. (generation, mixing, etc.)	60	3.23	1.170

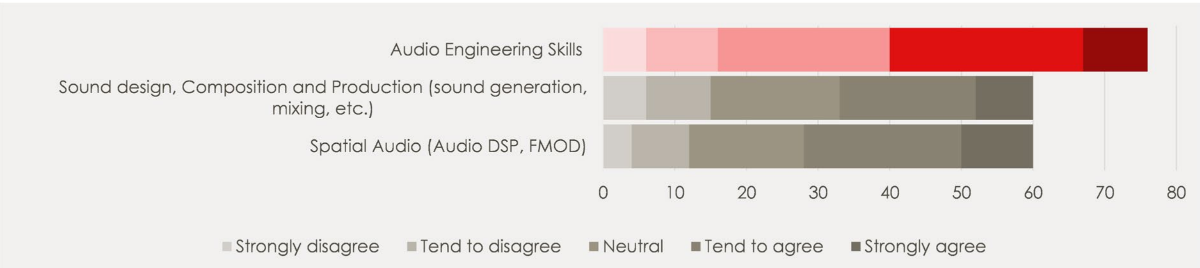


Figure 17. Audio Engineering Skills

As we can see from table 22 and graph 17, the category of audio engineering is not seen as very important. It is a surprise, because of the use of auditory displays to enable eyes-free mobile interaction in audio-augmented environments[64] (Vazquez-Alvarez et al., 2016). Using audio engineering allows users to explore an acoustic virtual environment augmenting a physical space, which is particularly useful when the users' visual attention is already being compromised by real visual objects in the surrounding environment. It seems that audio engineering skills are undervalued by the respondents despite the fact that there have been many demonstrations of audio augmented realities.

Human - Computer Interaction Skills

In our ninth question, we asked about HCI skills. Human-Computer Interaction (HCI) is about understanding what it means to be a user of a computer, and therefore how to create related products and services that work seamlessly. Those skills are crucial to create authentic experiences for AR users. There are many skills that we included into this category:

- Speech interaction
- Eye gaze tracking/interaction
- Gesture interaction
- User interface design
- User-centred design
- Design tools
- Basic artistic/design skills

Table 23. HCI Skills

Skills	N	Mean	Std. dev.
HCI Skills	76	4.17	0.870
Speech interaction	66	3.82	1.080
Eye Gaze tracking/interaction	66	4.00	1.023
Gesture interaction	66	4.11	0.979
User interface design	67	4.45	0.744
User-centred design (Accessibility, Universal Design, UX, Usability)	66	4.30	0.928
Design tools (Adobe Creative Suite, InVision, whiteboards, etc.)	65	4.00	1.016
Basic artistic/design skills (hand sketching, illustration, etc.)	66	3.82	0.991

[64] Y. Vazquez-Alvarez (2016) 'Designing Interactions with Multilevel Auditory Displays in Mobile Audio-Augmented Reality'

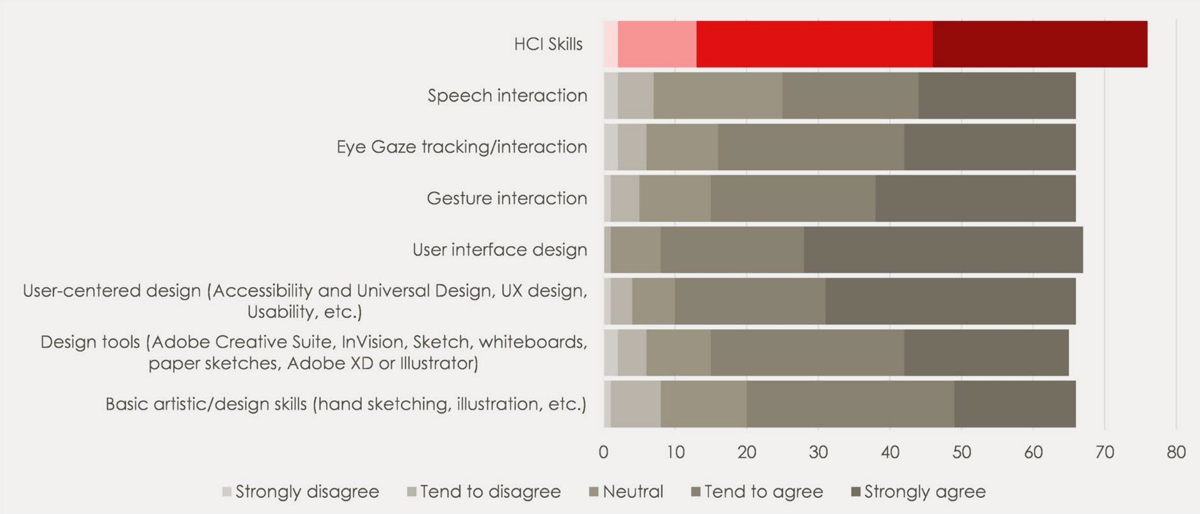


Figure 18. HCI Skills

From table 23 and figure 18, we can see that the categories - user-centred and user interface design are seen by respondents as the most important HCI skills (with means respectively 4.45 and 4.30). User-centred design (UCD) is an iterative design process in which designers focus on the users and their needs in each phase of the design process. User interface design (UI) is the design of user interfaces for machines and software with the focus on maximising usability and the user experience. The importance of the above skills can be explained via the idea that the entire world can be a user interface[65].

Hardware and Hardware-related Skills

Alongside the software the knowledge of hardware is necessary for AR specialists. Therefore, we asked for hardware and hardware-related skills:

- AR Smart Glasses
- AR projection solutions
- Optical design
- Maker skills
- Robots
- Internet of Things
- Sensors
- Wearables
- Signal processing
- Drivers, Hardware Abstraction Layer.

Table 24. Hardware and Hardware-related Skills

Skills	N	Mean	Std. dev.
Hardware and Hardware-related Skills	76	4.18	0.962
Drivers, Hardware Abstraction Layer (HAL)	64	3.59	1.019
Signal processing (for context sensing or for sensor fusion)	65	4	1.031
Wearables	67	4.06	1.043
Sensors	66	4.18	0.975
Internet of Things	66	4.03	0.911
Robots	66	3.52	1.085

[65] A. B. Craig (2013) 'Understanding augmented reality: concepts and applications'

Maker skills (3D printing, Arduino, microcomputers)	65	3.69	1.014
Optical design (Optical design software, optics, and frames)	64	3.55	1.167
AR projection solutions	67	3.88	0.896
AR Smart Glasses (HoloLens, Epson, Magic Leap, Meta One, etc.)	67	4.36	0.792

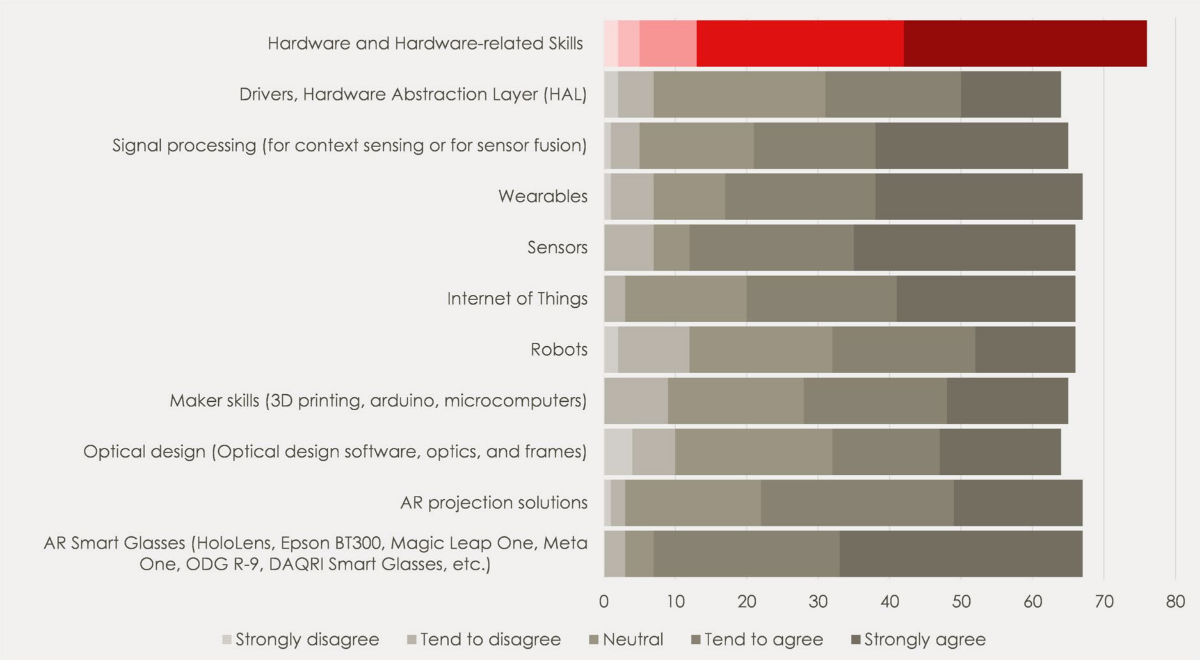


Figure 19. Hardware and Hardware-related Skills

Smart glasses were ranked the highest in this category as we can see in table 24 as well as in figure 19. Smart glasses are wearable computer glasses that add information alongside or to what the wearer sees. Smart glasses are becoming one of the most popular head-mounted display. For example, in a learning environment[66] they allow for high quality augmented reality experiences, which can overcome the perception gap and simultaneously avoid a split attention effect. Smart glasses can be used to provide targeted personalised coaching experiences [67] through a family of gamified AR applications. Schmalstieg and Heller[68] predict that in the future wearable computers will become a permanent part of our apparel, and may be seen as extension of the body generating 'augmented humans'.

Beside smart glasses also sensors were ranked very highly. Mobile devices are usually equipped with multiple sensors (GPS, magnetometers, linear accelerators) which are used to obtain prior information in outdoor localisation. When the aim of an AR application is to augment an existing image, then the sensor itself is the camera that produced the image, which is used as input data for computing the parameters to enable AR[69]. There is no way of creating an AR application without the use of sensors.

[66] M. P. Strzys (2018) 'Physics holo.lab learning experience: Using Smartglasses for Augmented Reality labwork to foster the concepts of heat conduction'
[67] R. Liu (2017) 'Feasibility of an Autism-Focused Augmented Reality Smartglasses System for Social Communication and Behavioral Coaching'
[68] D. Schmalstieg and T. Höllerer (2016) 'Augmented Reality Principles and Practice'
[69] A. Pagani, J. Henriques and D. Stricker (2016) 'Sensors for Location-Based Augmented Reality the Example of Galileo and Egnos'

6.3. Summary of the Categories of Skills

Overall Comparison of the Categories of Skills for AR Specialists

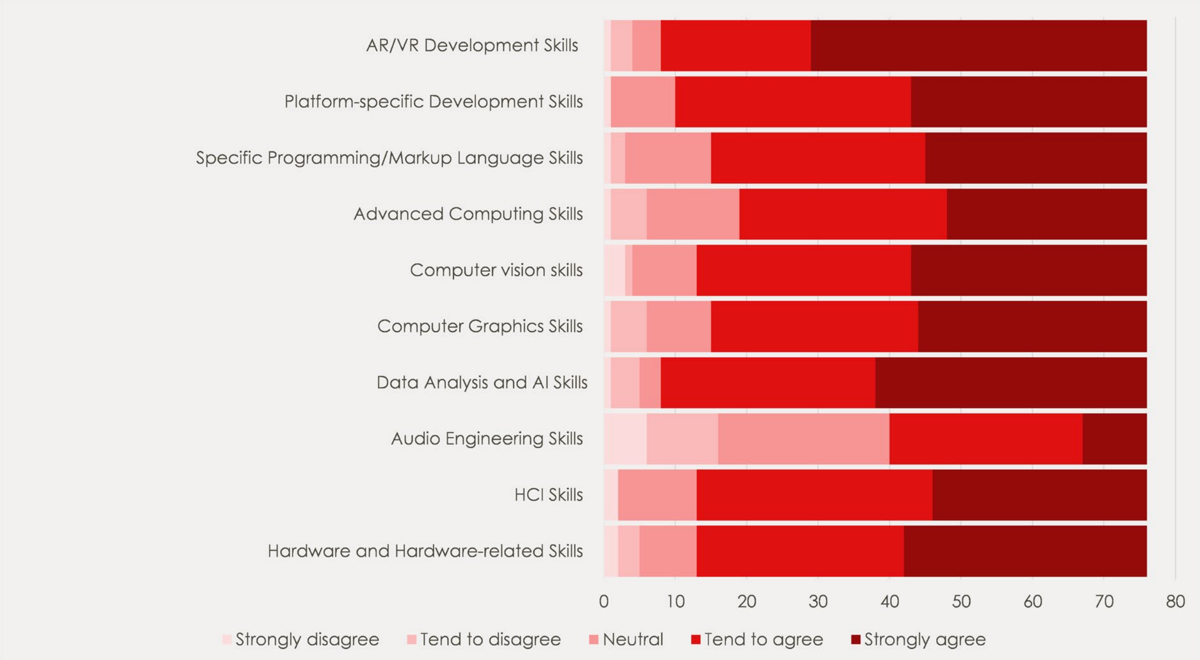


Figure 20. Categories of essential skills for AR specialists

In figure 20, we present all the main categories of AR skills we investigated. We can clearly see that almost all the identified AR skills are seen as important. Only audio engineering skills were less appreciated. For all the other skills, if we combine the number of answer where participants agreed and strongly agreed, we get results between 75% and 90 %. That confirms the choice of the skills that were extracted from the job announcements as required by the industry. Those skills should be implemented into the training of the future AR specialists.

Comparison of the Skills Valuation Depending on Position in the Company

In table 25 below, we have a comparison of how the key skills were valued by different professional groups: managers, professionals, technicians and academics. The counts for answers 'agree' and 'strongly agree' were added and the percentage for each group was calculated. The raw numbers are presented next to the percentages (Table 25).

Table 25. Valuation of the AR skills depending on position in the company

Position	managers		professionals		technicians		academics	
AR/VR Development Skills	96%	24	83.3%	30	100%	7	87.5%	7
Platform-specific Development Skills	96%	24	77.8%	28	87.5%	6	86.7%	8
Specific Programming/Markup Skills	76%	19	80.6%	29	71.4%	5	100%	8
Advanced Computing Skills	80%	20	75%	27	57.1%	4	75%	6
Computer vision skills	92%	23	77.8%	28	85.7%	6	75%	6
Computer Graphics Skills	88%	22	75%	27	85.7%	6	75%	6
Data Analysis and AI Skills	96%	24	83.3%	30	85.7%	6	100%	8
Audio Engineering Skills	44%	11	44.4%	16	57.1%	4	62.5%	5

HCI Skills	76%	19	86.1%	31	71.4%	5	100%	8
Hardware and related Skills	84%	21	80.6%	29	71.4%	5	100%	8

Managers value almost all the skills higher than professionals (except Specific Programming / Markup Language Skills and HCI Skills). Technicians value very high AR/VR Development Skills and academics value Data Analysis and AI Skills.

Most respondents can be qualified into two groups: managers and professionals. We focus then on the comparison of these two groups because it gives us the best overall picture. Managers value almost the skills higher than professionals. Only language skills and human-computer interaction skills are valued higher by professionals than by managers. Fisher's Exact Test was performed to compare those two main groups. Nevertheless, the significant difference between professionals and managers was not found in any category of skills.

6.4. Missing Skills

Respondents were also asked to propose the skills for an AR specialist in their organisation that they think were still missing in the questionnaire. 17 people (22 %) filled this question and suggested some more skills that they find important.

Missing Technical Skills

Some people asked for more specific, technical skills, some of them more general, some more connected with AR:

- 3D UX for AR/VR
- Location anchoring
- Quality and context modelling and assessment
- Solid mathematics skills, in particular for what concerns discrete mathematics and goniometry
- Process modelling
- Monitoring skills
- Software architecture
- Software Modelling (UML, Domain-Driven Design)
- Distributed computing
- Distributed systems
- Experimental design for testing
- Computer vision
- Knowledge of visual and auditory psychophysics

The importance of user experience and how that experience can affect the performance of the product was emphasised.

Missing Artistic and Soft Skills

There were demands as well for artistic and soft skills:

- Artistic background (in that it makes conversation between delivery and art direction teams more productive and co-respectful)
- Digital storytelling
- Phenomenology
- Psychology
- User learning styles
- Creativity and design
- Collaborative work skills

Missing Methodology Skills

The following methodology-related skills were mentioned:

- Prototyping
- Mock-ups
- Interoperability
- Alternative creative, artists and deconstructing preconceived perceptions of immersive technology and how it's all connected and not in isolation, across all verticals of education
- Communication and collaboration skills

Other Missing Skills

A few people noticed the significance of computational thinking skills:

- The basic CS skills that are unavoidable for someone to understand what computing means, what you can (easily) do and cannot (easily) do with computers and eventually to be in a position that enables you to learn by yourself all the other skills (including AR ones))

Project skills:

- The importance of the concept
- The importance of presentation and the ability to develop the project as part of a multidisciplinary team and with time constraints
- Creating an environment where students can develop and be aware of the importance of these (less technical) skills is a relevant part of the formation of AR specialists.

One person remarked the importance of the knowledge of policy:

- Training AR architects to comply with EU General Data Protection Regulation (GDPR)

7 Discussion and Recommendations for Teaching AR

After analysing all the results of the survey, we can identify the skills that are seen as important for future AR specialists:

- AR SDKs are more important than VR SDKs skills, Unity is more important than Unreal
- Multi-platform development skills
- Web front end and procedural programming the most important
- Software optimisation and instrumentation techniques and multi-threaded programming
- Object detection and computer vision
- Interactive 3D graphic design, 3D modelling and Generic CG & VFX
- Machine learning and artificial intelligence
- Audio engineering is not seen as very important
- User-centred and user interface design
- Smart glasses and sensors.

Those skills are the core skills that could be included in a programme of a course teaching AR specialists. Nevertheless, it is not an ultimate list. The aim is rather to create a form of declarative guidance for the education of future AR specialists, not a prescriptive register. Some of the skills are very advanced, those would be taught on advance courses. The basic course would rather focus on formation of expertise in software development tools that allows the creation of AR applications.

The figure below presents the 'top 10 skills'. The skills with the highest number of answers 'agree' and 'strongly agree' were chosen as the most important. They are presented as a percentage.

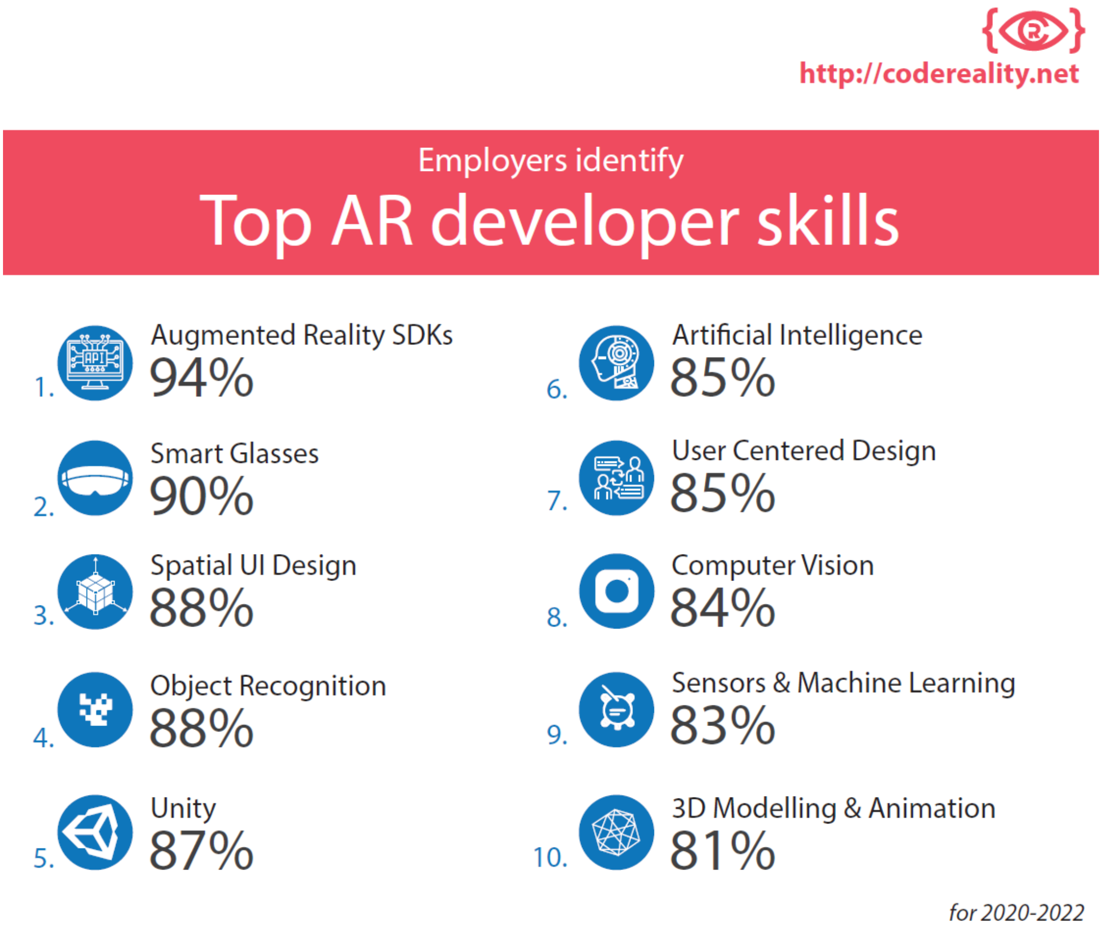


Figure 21. Top Augmented Reality Skills

The results of this survey will aid in the development of a Higher Education module aimed to train AR developers. The main objective of the Higher Education module will be to prepare professionals for the creative and digital industries of tomorrow and contribute to making economies more research-intensive, knowledge-based, and competitive.

8 Overall Conclusions

This report "Existing Teaching Practices and Future Labour Market Needs in the Field of Augmented Reality" aimed to better inform various stakeholders interested in the topic.

Specifically, we would like to attract the attention of education policymakers on organisational, national and international levels to read the report and the multiple survey studies conducted on the topic of using AR as a learning tool. This report on Augmented Reality education should help ensure that it is easier to make informed policy decisions that improve the educational offers on the topic and help stimulate capacity building in the field.

The result presented in this report will contribute to the global knowledge base of Augmented Reality education and professional skills that are currently valued by the industry. We hope that this report will contribute to filling the gap that exists in teaching Augmented Reality as a subject.

The authors of the report, in the frame of the AR-FOR-EU project, will actively use these results to design a new educational offer on the topic of Augmented Reality and multiple associated open educational resources.

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