A Review of Milgram and Kishino's Reality-Virtuality Continuum and a Mathematical Formalization for Combining Multiple Reality-Virtuality Continua

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Abstract—**We explore in this paper theoretical contributions that are related to Milgram and Kishino's Reality Virtuality Continuum by conducting a systematic literature review. From this study, we draw inspiration for our proposed mathematical formalization of combining multiple Reality-Virtuality Continua in a single, mixed reality experience. Also, we provide a definition for *XR transition protocol*. To complete our contribution, we discuss two potential examples that will exemplify our formalization and identify future work to be addressed.**

***Keywords*—Systematic literature review; reality-virtuality continuum; mixed reality; transitional interfaces; mathematical formalization; XR transition protocol**

I. Introduction

In 1994, Milgram and Kishino [1] introduced the Virtuality Continuum, an imaginary axis having real and virtual as its opposite ends. In the next year, the axis was renamed as Reality-Virtuality Continuum [2] (RVC), the name in use today. While introduced this Continuum, they also defined the "Mixed Reality" term as being anywhere between the extrema of this continuum. At the same time, the "Augmented Reality" term was introduced as the augmentation of real with virtual objects, and also "Augmented Virtuality" referring to the augmentation of virtual with real objects.

Since it's introduction in 1994, Milgram and Kishino's RVC has been widely cited and used by researchers (according to Google Scholar, at the time of writing this paper, the paper published in 1994 was cited 7540 times, and the follow-up paper from 1995 was cited 4133 times[1]). However, many papers built upon on this continuum to introduce or to develop XR systems; see next section for details. There were also some papers that used this continuum to expand their work by introducing new formalizations, conceptualizations or even for redefining Mixed Reality; a specific type of contribution is represented by the concept of traversable or transitional interfaces [3], in which a user can navigate, manipulate, and transit to other mixed reality experiences with a different level of augmentation, *i.e.*, different points of the Reality-Virtuality Continuum or other conceptual spaces.

Traversing or exploring this continuum was already addressed in scientific literature. For example, in 1999, Milgram and Colquhoun [4] formalized the transitions in RVC; also, Grasset *et al.* [5], [3] addressed this topic in both practical and theoretical ways. A few years later, Roo *et al.* [6] introduced a taxonomy for transitioning RVC, while Jetter*et al.* [7] proposed his own definition for *transitional interfaces*. Recently, Pampară and Vatavu introduced the concept of a journey in ARTV Continuum [8] as a transition between two points of this continuum, that is a 2D space where the vertically axis represents Milgram's RVC and the horizontally axis is also Milgram's RVC, but used in the context of Television. Hence, they invited participants of their experiment to view and explore the same video in four different augmentation levels; see [9] for details, and section III for details regarding previous work on transitional interfaces.

While the scientific literature explores the concept of traversable or transitional interfaces, these contributions involve experiencing different levels of augmentation and immersion of the same application, *i.e.*, on the same RVC. We propose in this paper to explore and formalize the possibility of combining multiple Reality-Virtuality Continua; to this end, such transitional interfaces allows transition not *on the same mixed reality experience*, but *between different mixed reality experiences*. To this end, we address the following research questions:

RQ_1. What theoretical contributions were introduced in scientific literature based on and related to Milgram and Kishino's Reality Virtuality Continuum [1]?
RQ_2. How can the identified theoretical contributions be classified?
RQ_3. Based on these findings, how can we formalize the combination of multiple Reality-Virtuality Continua?

In line with these research questions, we make several contributions, as follows:

1) We conduct a Systematic Literature Review (SLR) in order to identify theoretical contributions that are related to Milgram and Kishino's Reality Virtuality Continuum and classify these contributions in three categories, such as (1) *extensions*, (2) *integrations* and (3) *analogies*.
2) Based on these findings, we introduce a mathematical formalization of combining multiple Reality-Virtuality Continua, and propose a definition for *XR transition protocol*, for which we discuss several potential applications.

[1] https://scholar.google.com/scholar?hl=ro&as_sdt=0%2C5&q=A+TAXONOMY+OF+MIXED+REALITY+VISUAL+DISPLAYS&btnG=

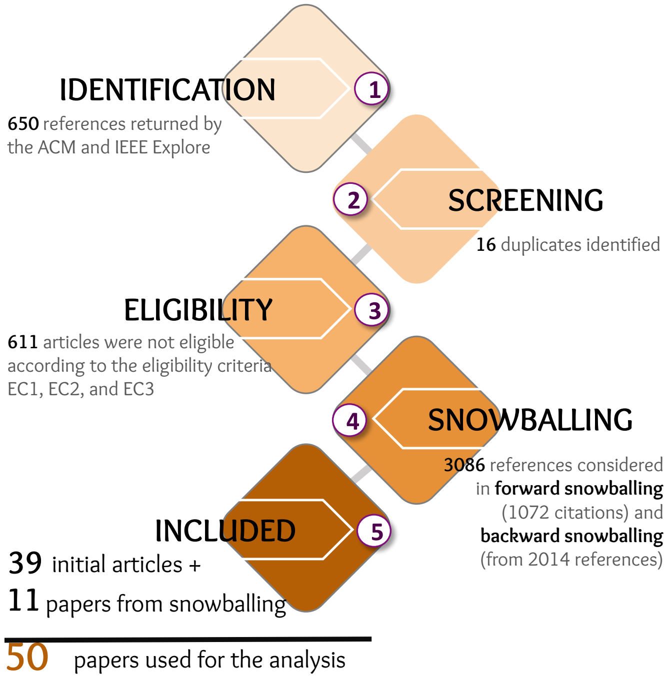

Fig. 1. The results of the *identification*, *screening*, *eligibility*, *snowballing*, and *inclusion* stages of our SLR.

II. Study Design

We conducted a Systematic Literature Review, for which we employed the Best Practice Guide [10], and implemented *identification*, *screening*, *eligibility*, *snowballing*, and *inclusion* stages. Fig. 1 presents the results obtained after each stage, illustrated using the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) diagram [11].

In order to identify keywords for our initial query, we examined Milgram's papers that introduces, discuss and explore Reality-Virtuality Continuum (RVC) [1], [2], [4]. To this end, in the *identification* stage, we searched for scientific paper relevant to our scope by using the following query [All: "reality-virtuality continuum"] OR [All: "virtuality continuum"] OR [All: "rv continuum"] AND [E-Publication Date: "(01/01/1995 TO 12/31/2022)"] for ACM Guide to Computing Literature[2] and the adapted version for IEEE Explore Database:"(("Full Text & Metadata":"reality-virtuality continuum") OR ("Full Text & Metadata":"virtuality continuum") OR ("Full Text & Metadata":"rv continuum"))", filtering only Conferences and Journals from 1995-2022 interval, as the most comprehensive bibliographic databases focused on the field of computing. The query returned 251 bibliographic results on ACM and 399 on IEEE Explore, resulting a total number of 650. During the *screening* stage, we read the abstract to determine their relevance to our scope of investigation. In this stage, we identified 16 duplicates and a retracted paper, remaining 633 results for the next stage. In the *eligibility* step, we read reach paper and used the following criteria to filter out results not relevant to our scope of investigation, *i.e.*, theoretical contributions related to Milgram and Kishino's RVC:

- EC_1: *The paper is academic* and underwent peer review. Magazine articles, workshop descriptions, proceedings descriptions, books, white papers, and tutorials were excluded. In this stage, 56 papers papers were excluded.
- EC_2: *The paper is about mixed reality.* We exclude all the results that referenced the RVC, but addressed other topics. In this stage, 25 papers were excluded.
- EC_3: *The paper presents a contribution that is directly related to the RVC instead of simply referencing it.* We excluded 512 papers in this stage, mostly presenting XR systems.

We used these eligibility criteria to identify peer-reviewed theoretical contributions that are directly related to Milgram and Kishino's RVC. After the eligibility stage, we arrived at a number of 39 relevant papers, for which we applied two snowballing procedures [12]: (1) *backward snowballing*, where we analyzed the references of all the eligible papers, total of 2014 papers, and (2) *forward snowballing*, where we analyzed their Google Scholar citations, total of 1072. From the *backward* stage, we identified 7 additional papers, and from the *forward* stage, we identified 4 additional papers that met our three eligibility criteria. Our final set of papers contains 50 academic papers published between 1998 and 2022. These papers were analyzed and the following information were extracted to address our research questions:

1) Contributions from papers that referenced RVC for introducing an *extension* of this continuum. An illustrative example for this category is represented by the recent revision of Milgram and Kishino's RVC introduced by Skarbez *et al.* [13]. We used this information to address RQ_1 and RQ_2.
2) Contributions from papers that used RVC in order to introduce an *integration* of RVC in other concepts, such as Vatavu *et al.* [8]'s ARTV or Jeon and Choi [14]'s visuo-haptic MR taxonomy. We used this information to address RQ_1 and RQ_2.
3) Contributions from papers that referenced RVC for introducing a theoretical contribution based on an *analogy* with this continuum. These papers didn't modify or alter this continuum, but employed correspondences or analogies with this axis, as Popoveniuc and Vatavu [15] did when introduced transhumanism: a philosophical and cultural framework for Extended Reality applied to Human Augmentation. We used this information to address RQ_1 and RQ_2.
4) Information about the *validation of the scientific contributions*, with five categories: (i) examples from *prior work*, *e.g.*, papers from scientific literature or prototypes from industry, (ii) *demonstration*, *e.g.*, working prototype or application without a user study, (iii) *user study*, *i.e.*, studies for valuable feedback on proposed systems involving representative end users, (iv) *implications*, *e.g.*, future implications or guidelines for future work, and (v) *no validation* at all; see Fig. 3. We used this information to complement our findings in relation to RQ_1 to RQ_2.

[2]https://libraries.acm.org/digital-library/acm-guide-tocomputing-literature

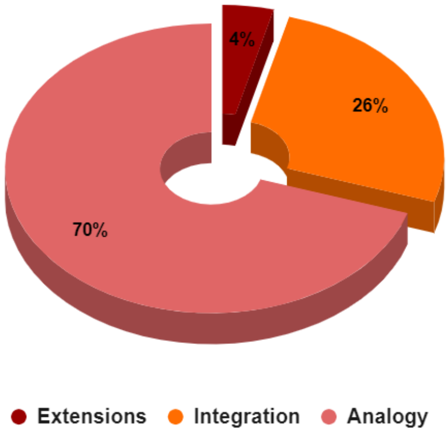

Fig. 2. Overview of contribution types of our extracted papers.

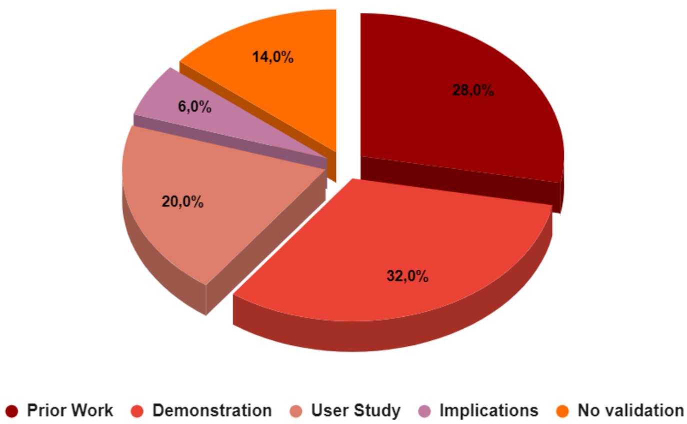

Fig. 3. Overview of validation types of our extracted papers.

III. Results

We present a meta-analysis of 50 scientific papers that proposed theoretical contributions directly related to Milgram and Kishino's RVC.

A. Extensions of RVC

In our investigation, we identify two papers that propose an extension of RVC. Firstly, Ridel *et al.* [16] introduced *revealing flashlight*, "a new interaction and visualization technique in spatial augmented reality that helps to reveal the detail of cultural heritage artifacts" [16, p. 1]. To this end, they proposed an extension of RVC to account for see-through and spatial augmented reality. In their extension, Augmented Reality from RVC is divided into Spatial Augmented Reality and See-Through Augmented Reality. In order to validate their extension and explore spatial augmented reality concept, the authors introduced "revealing flashlight" prototype which is configured to augment a real artifact at a fixed location, by using one single video-projector. Also, they identified three characteristics involved in using a classical flashlight for illuminating an object, such as (1) spot, corresponding to the illuminated spot of the flashlight's lighting cone, (2) distance, corresponding to the distance between the flashlight and the illuminated point on the surface, and (3) the angle between the light direction and the normal of the illuminated point on the surface.

Another important extension was introduced by Skarbez *et al.* [13], who revisited Milgram and Kishino's Continuum, proposing an alternative definition of mixed reality. Their work started by extending the discussion from only visual displays, to "the multiple senses" [13, p. 2], including interoceptive (that monitor the body's internal state) and exteroceptive senses (that responds to stimuli that come from outside the body). To this end, the authors argues that "there is a discontinuity on our revised continuum, because true virtual reality exists only when all senses - exteroceptive and interoceptive - are fully overridden by the computer-generated content" [13, p. 4]. As an example of pure virtual reality, the authors mentioned the Matrix films, where both interoceptive and exteroceptive senses are stimulated by the technology. In this new light, the Milgram and Kishino's Virtual environment became External Virtual Environment, and the pure virtual environment was named as "Matrix-like" Virtual Environment. One of the limitations of the Milgram and Kishino's RVC that Skarbez *et al.* [13] identified is the absence "of an observer or a user with senses other than visual and prior life experiences", arguing that "the notion of an environment without an experiencing being - the aforementioned observer - is incomplete"; therefore, "the mediating technology, content conveyed, and resulting user experience must be considered together to adequately describe MR experiences" [13, p. 2]. To this end, they proposed a revised definition of a Mixed Reality environment, "in which real world and virtual world objects and stimuli are presented together within a single percept" [13, p. 4].

B. Integrations of RVC

We identified some papers that integrate the RVC axis into new concepts; such theoretical contributions can be classified into two categories: (1) concepts, definitions and taxonomies, and (2) design spaces or conceptual frameworks.

1) Concepts, Definitions and Taxonomies.: A few papers from our SLR introduced concepts, definitions or taxonomies, and some of them were proposed for different types of mixed realities. For example, Steve Mann [17] defined the term mediated reality and for a better understanding, he proposed the taxonomy of Reality Virtuality Mediality Continuum, that is a two orthogonal continua, where the horizontal axis is represented by RVC and the vertical one represents Reality Mediality continuum. Kubota *et al.* [18] proposed the concept of Transformed Reality as a new approach that alters users' perception of the world using computation, into a form that the user prefers. They introduced the level of transformation axis when integrating Transformed Reality in RVC. They also proposed an algorithm for edge and shadow extraction, and used it in a new system, "Anime Glasses", that converts natural scenes into anime style in real time. Finally, Pamparău and Vatavu [9] proposed a definition for a journey in ARTV continuum [8] as a transition between two points of this continuum, that is a 2D space where the vertically axis represents Milgram's RVC and the horizontally axis is also Milgram's RVC, but used in the context of Television.

2) Design Spaces or Conceptual Frameworks.: In our investigation, we found papers that proposed conceptual frameworks or design spaces by integrating the RVC axis. For instance, Kraus *et al.* [19] addressed human-human communication during the use of immersive teleoperation interfaces. Their work was based on real-life examples by introducing classification that consists of a 2D space, one for *copresence* (single user teleoperation by an immersed user communicating with a non-immersed user, collaborative teleoperation by two connected, immersed users, and joint teleoperation by two colocated, immersed users), and one for *virtuality*, *i.e.*, Milgram's RVC axis. When introducing Haptic Augmented Reality, Jeon and Choi [14] proposed a visuo-haptic Mixed Reality taxonomy, which consists of two orthogonal reality-virtuality continua, one from visuals and one for haptics. Another two dimensional framework is represented by virtual environments for advanced modeling (VEAM) [20], which is the intersection of Milgram's RVC and Advanced Modeling Techniques, such as (1) mental models, (2) models and representations, (3) and metaphors and theories.

Some papers proposed conceptual frameworks or continua that consists of more than two dimensions. For instance, Stapleton *et al.* [21] broke down the Milgram's RVC in two dimensions, *i.e.*, Physical Reality (the venue), and Virtual Reality (the content), that combined with Imaginary Reality (the story), results in Compelling Mixed Reality (the play). This new resulting spaced was named as Mixed Fantasy Continuum. In a follow-up work, Stapleton *et al.* [22] proposed a new dimension for RVC, Imaginality, that is able to produce its own internal perception to influence the external perception of Physical and Virtual Reality. Williams *et al.* [23] proposed the Reality-Virtuality Interaction Cube, a three dimensional continuum which combines the Plane of Interaction, a framework for characterizing interactive technologies in a 2D spaced informed by the Model-View-Controller design pattern, and the Milgram's RVC, while Lee *et al.* [24] introduced the Ubiquitous VR Space, a 3D space that consists of: (1) Milgram's RVC, (2) Static-Dynamic Context Continuum, and (3) Personal-Social Activity Continuum. Recently, Guan *et al.* [25] introduced the domain of an Extended Metaverse Agent based on a combination of Milgram's RVC and the MiRA cube, for which two prototypes were proposed, and Vatavu [26] addressed Sensorimotor Realities by proposing a six-dimensional conceptual space: (1) Sensory Mediation, (2) Motor mediation, (3) Virtuality, (4) Imaginarity, (5) Body augmentation, and (6) Environment augmentation.

C. Analogies with RVC

Most of the theoretical contributions that we identified in our SLR were introduced as a correspondence, or an analogy with RVC. In this category, we identified 70% of our papers; see Fig. 2 for a visual representation. Same as in Section III-B, we classified these contributions in a few categories, such as (1) *spanning* or *transitions* between different states of conceptual spaces, (2) *definitions or concepts*, (3) *taxonomies, conceptual frameworks or design spaces*, and (4) *other* forms of theoretical contributions; see next.

1) Spanning or Transitions between different states of Conceptual Spaces.: There are some works that proposed the possibility of exploring transitions in different design spaces, an idea that was addressed for the first time more than 20 years ago, when Koleva *et al.* [27] introduced the concept of mixed reality boundaries, and also traversable interfaces (boundaries) as a particular example. These interfaces are able to "provide a mechanism for people to dynamically relocate themselves along this [Milgram's RV] continuum" [27, p. 156]. In the same year, Koleva *et al.* [28] formalized the concept of traversable interfaces, which creates the illusion that physical and virtual worlds are blended together so that users can physically cross between them, repositioning themselves along the reality-virtuality continuum. According to the authors, at one moment they could be primarily located in either augmented reality or augmented virtuality, "according to their interest and whether they want the physical or virtual to be their primary focus" [28, p. 233]. Roo and Martin [6] proposed a conceptual framework to allow incremental transition from pure physical to pure virtual experiences in a unique reality. This framework consists of six levels, such as (1) physical world, (2) augmented surfaces, (3) mid-air digital content, (4) object decoupling, (5) body decoupling, and (6) pure virtual world.

This topic was also addressed in the last couple of years. For instance, George *et al.* [29] defined the user possibility to explore transitions between Milgram's RVC states without taking the headset off as *seamless transition* concept (SeaT), proposing a design space for further investigating of seamless, bi-directional transitions, that consists of four dimensions, such as (1) motivation for transition (social interaction and collaboration, physical integrity & orientation, awareness, and interaction with physical & virtual objects), (2) availability (user-triggered, system-triggered and continuous), (3) modality (visual, audio or haptic), and (4) the act of transitioning itself. By exploring to the same concept, Jetter *et al.* [7] introduced Transitional Interfaces (TI) term, that enable users to move between different locations within the RVC; TIs allows users to choose the technology that best supports the task at hand and fulfills their information need. Finally, last year Wang *et al.* [30] proposed a design space for single-user cross reality applications that consists of four dimensions: (1) transition and concurrent usage (a user transits from one point on the RVC to another, a user moves a visualization from one point on the RVC to another, a user interacts with multiple systems that belong to different points on the RVC concurrently), (2) output device, (3) input device (interacting with multiple systems along the RVC, interacting with one system along the RVC), and (4) interaction (transiting to another reality, moving a visualization across realities, selecting object across realities, and manipulating object across realities).

There are also works that introduced transitional interfaces by means of demonstrative applications. For example, Billinghurst *et al.* [31] focused on the implementation of MagicBook, the first example for transitional interfaces concept. Also, Casas *et al.* [32] introduced the concept of Multi-Reality Games that encompasses interactions with real and virtual objects to span the entire spectrum of RVC.

2) Definitions or Concepts.: Milgram's Reality-Virtuality Continuum was a source of inspiration for more than 25 years. For instance, in 1998, Raskar*et al.* [33] introduced a new concept, Spatially Augmented Reality (SAR) that describes realities where virtual objects are rendered directly within or on the user's physical space. A few years later, Huynh*et al.* [34] defined Blended Reality (BR) as "the realm where the real and virtual worlds blend together as one space, letting users and real objects interact with virtual objects in a direct and physically natural manner" [34, p. 894]. The concept of blended reality was also discussed by Robert *et al.* [35], defining it as "extending mixed reality, enabling the fluid movement of blended reality characters between the fully virtual and the fully physical" [35, p. 361].

From the papers that present analogies with RVC, we found contributions on multimodal AR or XR. For instance, Rosa *et al.* [36] introduced three concepts for an understanding of multimodal AR: (1) redefinition of 'real' and 'virtual' in terms of stimuli, (2) a new analysis of AR based on current definitions - combination of a basis and an augmentation, instead of combining real and virtual, (3) a classification system for different forms of multimodal MR for the basis-augmentation model. When trying to define XR, Rauschnabel*et al.* [37] employed prior work on XR and qualitative insights from XR professionals. They proposed a few propositions and a new conceptual framework. First, they "posit that X - in XR - represents a placeholder (similar to an X variable in algebra) for any form of new reality" [37, p. 5]. Then, when refining AR and VR, they started from the question: "Is the physical environment, at least visually, part of the experience?" [37, p. 6] If the answer is Yes, than AR is defined as a continuum (Assisted-Mixed-Reality Continuum) where local presence is located between Assisted Reality (left) and Mixed Reality (right) extremes; this categorization depends on the level of local presence perceived by the user. If the answer is no, then VR is revised as a continuum where telepresence is located between Atomistic Virtual Reality (left) and Holistic Virtual Reality (right) extremes; this categorization depends on the degree of telepresence perceived by the user. Finally, they proposed new definitions for Augmented Reality, as "a hybrid experience consisting of context-specific virtual content that is merged into a user's real-time perception of the physical environment through computing devices" [37, p. 13] and Virtual Reality, as "an artificial, virtual, and viewer-centered experience in which the user is enclosed in an all-encompassing 3D space that is - at least visually - sealed off from the physical environment" [37, p. 13].

3) Taxonomies, Conceptual Frameworks or Design Spaces.: Inspired by Milgram and Kishino's RVC, Benford *et al.* [38] proposed a taxonomy for classifying approaches to shared spaces according to the three dimensions of transportation, artificiality, and spatiality. Lindeman and Noma introduced a continuum ranging from the physical environment to the human brain, which could be called as "where the mixing of real and computer-generated stimuli takes place" [39, p.], while Grasset *et al.* [5] conceptualized the Physicality Continuum that applies to Books. The main points of this continuum are: (1) Virtual Book, (2) Virtual Augmented Book (traditional AR Book), (3) Mixed Reality Book, and (4) Real Book. Speicher *et al.* [40] employed a series of interviews with domain experts and made a literature review, proposing a conceptual framework for Mixed Reality composed of seven dimensions: (1) Number of Environments (one, many), (2) Number of Users (one, many), (3) Level of Immersion (not, partly, fully), (4) Level of Virtuality (not, partly, fully), (5) Degree of Interaction (implicit, explicit), (6) Input (any), and (7) Output (any).

Theoretical contributions were also proposed in the field of Augmented or Mixed Reality. Based on the existing taxonomies that they identified in scientific literature, Normand *et al.* [41] introduced a new taxonomy composed of four axis: (1) number of degrees of freedom of the tracking required by the application and the tracking accuracy that is required, (2) augmentation type (augmenting the world, or augmentation is linked to the user), (3) application-based, covering the temporal base of the displayed content, and (4) rendering modalities that go beyond visual AR. Hirzle *et al.* [42] conceptualized a 2D design space for gaze-interaction: the first dimension D1 (y-axis) is used to classify HMD technology; this is composed of device type (VR or AR), display type (monoscopic or stereoscopic), and word knowledge (full/none). The second dimension, D2 (x-axis) is composed of two parameters: oculumulator depth cue (vergence/accommodation) and ocularity (monocular/binocular). Also, Phaijit *et al.* [43] formalized a 3D taxonomy for AR-for-HRI: perception augmentation (augmented human perception and augmented robot perception), functional role of AR (artificial timescale, augmented comprehension of the present reality and augmented control) and augmentation artifact type (augmented embodiment, augmented interactive objects, augmented user interface and augmented scene). When exploring the field of ARTV, Saeghe *et al.* [44] conducted a SLR from which identified six themes and a set of cross-cutting design decisions. Also, they used these themes for proposing a design space with six dimensions: (1) abstraction, (2) interaction, (3) time, (4) display, (5) context, and (6) editorial control. Finally, Holz *et al.* [45] introduced the notion of Mixed Reality Agents (MiRA), which are defined as agents embodied in a Mixed Reality Environment. Also, they introduced a taxonomy that classifies MiRAs along three axes: (1) agency (based on weal and strong notions outlined by Wooldridge and Jennings in 1995 [46]), (2) corporeal presence (the degree of virtual or physical representation of a MiRA), and (3) interactive capacity (the ability to sense and act on the virtual and physical environment).

In our investigation, we identified more diverse contributions. For instance, Chuah *et al.* [47] formalized the idea of Embodied Conversational Agents (ECAs) for which proposed a taxonomy that consists of two dimensions and 7 subdimensions, such as (1) Occupancy of the Physical Space (that consists of (1.1) Size Fidelity, (1.2) Position Fidelity, (1.3) Form Fidelity, (1.4) Concordance with the Physical Space, and (1.5) Range of Valid viewpoints subdimensions), and (2) Interaction with the Environment (that consists of (2.1) ECA's Awareness of Changes to Environment, and (2.2) ECA's Ability to Change Environment subdimensions). Genay *et al.* [48] proposed a taxonomy of virtual embodiment experiences by defining "body avatarization" continuum, from Real Body, to Body Accessorization, Partial Avatarization and Full Avatarization. In addition, the authors presented the methods that exist to measure Sense of Embodiment (SoE) in AR and then illustrated current knowledge on the factors of influence of the SoE in AR. Recently, Popoveniuc and Vatavu introduced transhumanism, as a philosophical and cultural framework by combining RVC, Mann's [49] mediators, Baudrillard's [50] concept of "hyperreal", and Sorgner's [51] version of Bostrom's transhumanist philosophy [52].

4) Other forms of Theoretical Contributions.: Finally, some of the papers selected in our SLR have different forms of theoretical contributions, and were inspired by Milgram and

Kishino's RVC. For example, Vatavu [53] introduced three postulations for understanding the overlap between Ambiental Intelligence (AmI) and AR, such as (1) the concept of an Environment that Undergoes Augmentation, (2) the mandatory process of an Integration Involving the Environment and (3) the emergence of media that reflects the characteristics of the Environment. In the end, the author identified three implications for Human Computer Interaction field: (1) Using AmI for Innovations in AR systems and Vice Versa, (2) Conjoint Application of AmI and AR Concepts and Technology, and (3) Cross-Device Interactions Across Wearables and Ambient Devices. By taking into account the cultural and social dimensions of MR experiences, Rouse *et al.* [54] focused on a class of applications defined primarily by the quality of the experience they provide, and only secondarily by the mediating technology, designating MR^x applications, where the superscript x is meant to mark the importance of user experience. Also, the authors introduce a 2D space for describing MR and MR^x concepts, where the horizontal axis represents a continuum from Locative, geolocated in a predetermined space, to Site-Specific, integrated into a place, while on the vertical axis, focus ranges from Information Transfer to Experience.

Müller [55] classified information in procedural tasks in AR into five layers: the real world, the mediated world, virtual objects that are spatially referenced and of spatial nature, virtual objects that are spatially referenced but not of spatial nature, and virtual objects that do not have any connection to the physical world, while Speiginer *et al.* [56] proposed the Environment-Augmentation framework in contrast to RVC, *i.e.*, "the Environment-Augmentation framework conceptualizes an immersive experience as the integration of layers of reality, whether or not these layers are real or virtual, explicit or implicit, tightly coupled or loosely coupled" [56, p. 328]. A new approach that aims to combine virtual and physical world in a novel way was introduced by Lindlbauer *et al.* [57] through the concept of Remixed Reality, for which a four-dimension taxonomy was proposed: (1) spatial modification (reshape, move/copy, erase, scale), (2) appearance modification (recolor, relight, artistic), (3) viewpoint modification (teleport, arbitrary movement, portals, and change projection), and (4) temporal modification (playback, pause, reverse playback, playback with changed speed, loop). A last contribution in our SLR was introduced recently by Dam *et al.* [58] when, informed by the conclusions of a workshop where the primary goal was to understand and define Audio Augmented Reality (AAR), the authors conducted a literature review on this field, and finally proposed a three dimensional space for AAR. This space is compound of (1) Immersion, ensuring that the sounds lead to enhanced perceptions or augmented experiences, (2) User context, meaning the information must be applicable and assistive to the user's primary task, and (3) Customization, meaning sounds may be audible to more than one user in the environment, but they are customized to be meaningful and unique only for the intended user. In the end, they proposed a definition for AAR, as "auditory information, customized for the intended user that is capable of sufficiently immersing yet retraining awareness of their environment and designed to provide appropriate assistance in the user's primary task." [58, p. 1223].

D. Validation of Scientific Contributions

We extracted information about the validation of the scientific contributions related to Milgram and Kishino's Reality-Virtuality Continuum; see Fig. 3. We found that 32% of the papers *demonstrated applications*. For example, George *et al.* [29] implemented a prototype for understanding how users interact with a seamless bi-directional transition solution and what effects does such a solution have on factors such as, presence, performance and safety. A percent of 28% of the papers discussed examples from *prior work* that demonstrate their theoretical contributions. For instance, after introducing a new taxonomy of augmented reality applications, Normand *et al.* [41] discussed different works from literature that populates the taxonomy. We found that 20% of the papers employed *user studies*. For example, Kubota *et al.* [18] conducted an experiment by using their proposed system, "Anime Glasses", and proposes other possible applications of Transformed Reality. We also identified a percent of 14% of the papers that didn't validate their contributions in any way, and a percent of 6% of the papers discussed implications after proposing their contributions. For example, Vatavu *et al.* [53] discussed AmI and AR fields and arguing that these two fields have things in common, proposing three postulation in this context, for which three implications for HCI were identified, such as the use of AmI or innovations in AR systems and vice versa, conjoint application of AmI and AR Concepts and technology, and cross-device interactions across wearables and ambient devices.

IV. Formalizing the Combination of Multiple Reality-Virtuality Continua

In this paper, our aim is to formalize a way in which two or more RVC continua can be combined into a single, mixed reality experience, according to our RQ_3. First, we conducted a SLR in order to identify all the theoretical contributions that were reported in relation with Milgram and Kishino's Reality-Virtuality Continuum. The results that were obtained were classified in three categories, such as *extensions*, *integrations* and *analogies*; see Fig. 2. We found papers that combined RVC with different dimensions, resulting in new concepts. An example of this type of contributions is Mediated Reality introduce by Steve Mann [17], where an axis is RVC, and the second axis is Reality Mediality Continuum; see Section III-B for all papers that fits in this category. Also, we found a few papers combining two RVC axes, but with different meanings. For instance, Jeon and Choi [14] combined two RVC continua, one for visual and one for haptic, while Vatavu *et al.* [8] combined two RVC continua, one for Television and one for the world being augmented. Next, we formalize the combination of more than two RVC axes, each of them consisting in a unique, different mixed reality experience. We draw inspiration from Milgram and Kishino definition of Augmented Reality, and Jetter's [7] concept of *transitional interfaces*.

In the definition of augmented reality reported by Milgram and Kishino [1], augmenting an environment implies *adding* (real or virtual) objects to it; generalizing, this can be rephrased as the existence of an *operation* between the environment and the objects that is augmented with (*i.e.*, addition). To this end, because of the simplicity of formalizing or explaining concepts in mathematical words, we choose to present the concept of combining multiple RV continua as transitional interfaces by using a generic function, for which the domain is defined as a repeated operation applied to RVC world, resulting a *perceptible* RVC world:

$$F_i : RV_1 \circ RV_2 \circ ... \circ RV_i \rightarrow RV, 2 \leq i \leq n, n \in N^* \quad (1)$$

where "$\circ$" denotes a possible operation that could exist between at least two RV continua. These functions describe In addition, each F_i function has a corresponding *XR transition protocol*, tp_i.

In order to clarify what form the operation could take, we will connect the previous work presented in subsection III with our model that we introduced.

A. F_2 Type Contributions.

If we apply the equation 1 for *n* = *2*, we obtain theoretical contributions, systems or applications that are described by

$$F_2 : RV_1 \circ RV_2 \rightarrow RV \quad (2)$$

, meaning that an operation was applied to two RV continua, resulting in a mixed reality experience. Prior work on this type of systems is limited and contains works that introduced a two orthogonal design space where both of the axes were represented by RV Continuum. For instance, when introducing ARTV Continuum, Vatavu *et al.* [8] combined two orthogonal axes, one for TV and one for real world. Jeon and Choi [14] introduced a visuo-haptic mixed reality taxonomy as an orthogonal space from two RV axes, one for visual and one for haptic. To this end, it can be stated that the operation that was applied to the RV axis for F_2 was cartesian product (2D orthogonal space), meaning that equation 2 becomes

$$F_2 : RV_1 \times RV_2 \rightarrow RV \quad (3)$$

B. Combining Multiple Reality-Virtuality Continua as a Transitional Interface.

Applying a cartesian product between two RV axes was useful and easy to understand and then to populate the introduced design space with examples from scientific literature. However, if we want to extend the number of RV continua, cartesian product is an expensive operation and, as Rosa *et al.* [36] states when discussing Jeon and Choi's [14] taxonomy, "it extends poorly to all modalities, since the complexity grows [when adding a 3^{rd} dimension] exponentially with each added modality" [36, p. 3]. A solution to that will consist of the consideration of a cartesian product as a transitional interface, *i.e.*, where the user will perceive sequentially each mixed reality, transitioning from one to another. Theoretically, a combination of three RVC axes (three different mixed reality experiences) could be modeled as a cube, for which a *XR transition protocol* should be specified. For a better understanding, and by capitalizing on our findings from section III, we also provide a definition for *XR transition protocol*:

> ***Definition:*** An *XR transition protocol* is a set of engineering - hardware and/or software - details that are employed by XR transitional interfaces.

An example of XR transition protocol is the one employed by Pamparău and Vatavu [9] for transitioning in different points of ARTV Continuum, that consisted in a keyboard connected to HoloLens HMD device via bluetooth and 1, 2, 3 or 4 keys that participants in their experiment used to transit between different level of augmentation, *i.e.*, different points in ARTV Continuum.

Since a combination of three RVC axes could easily be modeled as a cube, we want to address the combination of more than three RV Continua in a different way. The F_4 will describe systems that employs four distinct mixed reality experiences, and by the use of a *XR transition protocol*, cross-reality leaps are possible; to this end, the user is experiencing a single reality, at a specific moment. Hence, the F_4 will be:

$$F_4 : RV_1 \times RV_2 \times RV_3 \times RV_4 \rightarrow RV \quad (4)$$

, with the corresponding tp_4 transition protocol that should be defined. In the next section, we discuss some potential examples of implementing (F_4, tp_4) systems.

V. Potential Examples of (F_4, tp_4) Systems

We present in this section two potential examples of implementing such (F_4, tp_4) systems that consist of 4 different mixed reality experiences that the user transit them by employing a specific tp_4 protocol. For both of the proposed examples, we draw inspiration from prior work.

Recently, the concept of SAPIENS-in-XR [59] was introduced, for which the authors employed a technical performance evaluation, where they "injected events in SAPIENS-in-XR architecture at random moments of time sampled from Poisson distributions with the rates λ = 10, 5, and 1, corresponding to different expected numbers of notifications occurring over a 5-second time interval" [59, p. 8]. In the same manner, a mixed reality system consisting of four different scenes (experiences) can be implemented and, a Poisson distribution could be used in order to generate random moments when the user could be notify about the transit possibility; in this way, on different moments of time, the user is able to switch his/her mixed reality experience, sequentially. For a better user experience, but also based on the field that mixed reality experience addresses, empirical studies could be performed in order to identify best parameters for the Poisson distribution.

Another potential example could be implemented by using one of Vatavu's [53] implications for Human Computer Interaction when discussing Ambient Intelligence and Augmented Reality, as two faces of the same coin. To this end, the same mixed reality application could be used (*i.e.*, that employs 4 different experiences), with a different protocol tp_4, for which we draw inspiration from Schipor's *et al.* [60] work that employed the existence of digital content in thin air. Returning to our example, the user wearing HMD will be placed in a smart environment in which localization data in three dimensions are available and collected with a Vicon Motion Capture system (www.vicon.com) with six Bonita cameras (1 Mp resolution and 100 fps for each camera). The HMD will have IR reflective markers attached that will give the exact location of the user. To this end, the physical space could be "decorated" with four different mixed reality experiences that are activated when the user arrives in their 3D location. For example, when the user arrives in (650,233,1450) 3D point, the IR reflective markers will send to Vicon this information, and the HMD will be notified of this aspect, rendering a specific mixed reality experience.

VI. Conclusion and Future Work

We started the investigation in this paper by conducting a Systematic Literature Review for identifying theoretical contributions that are directly related to Milgram and Kishino's Reality-Virtuality Continuum. Based on the obtained results, we formalized the concept of combining multiple Reality-Virtuality Continua into a single mixed reality experience. Inspired by prior work, we also provided two examples of potential applications that could be implemented as instances of our formalization. Future work will involve explorations and implementations of integrating different numbers of Reality-Virtuality Continua, with different XR transition protocols.

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