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Preserving theoretically-grounded functions across media platforms in interaction design

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Designers often address the continuity of user experiences across various media platforms, with preservation of functionality in mind. But the media dependency of features means that successfully preserving the essence of one feature across media platforms, in a process of cross-media translation, can actually result in features that appear dissimilar. We describe function mapping as an aid in this translation, in which design specifications are derived from theoretical assertions. A theoretical understanding of underlying functions permits the subsequent translation of features to other media platforms. We demonstrate this in a case study of translation from a VR installation, to portable VR, and then to a website. We also compare similar environments on the same media platform: one website that was developed through function mapping, and one that was not. This crystallizes the impact of function mapping, which achieves a theoretical form of equivalency across media platforms.

Keywords: multimedia design; cross-media design; theory-driven design; virtual reality

1 Introduction

As digital media technologies proliferate, it is increasingly common for designers to address the continuity of user experiences across media platforms. The global pandemic is an extreme example of the value of designing across media: educators at all levels of instruction had to rapidly redesign their instruction for an online format, relying on new methods to preserve as much as possible from learning experiences that were previously dependent on other methods. In media development, features are the focus of design, but their specification is often media-dependent, and it is not always straightforward how the essence of one feature might be preserved when it is adapted to a new media platform. Doing so requires the designer to recognize the underlying function of the feature, as separable from how that function is expressed in its platform dependence. Function mapping is a technique we devised in which development teams utilize theoretical assertions from a relevant body of literature to guide design decision-making.

Theoretical assertions about design are readily available. For instance, Mayer's (2001) multimedia learning theory includes principles that can guide decisions about layout — the spatial contiguity principle suggests that related text and pictures should be near one another. In contrast, function mapping addresses theoretical assertions from a non-design domain that do not provide direct guidance for design decisions (Figure 1), operating on knowledge that has yet to be applied to design. Function mapping is translational, isolating theoretical assertions so that once designers operationalize those assertions in features, they can track purpose through evaluation and for further development. What a theoretical assertion claims can be carefully assessed according to the distinct set of features designed to address it.

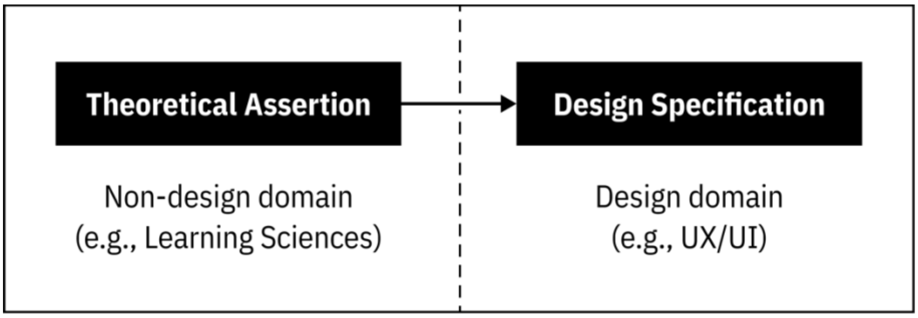

Figure 1. Function mapping is a technique in which designers translate theoretical assertions from non-design domains into specifications in a design domain.

We originally used function mapping as a theory-driven form of multimedia development for making decisions in the design domain based on assertions in the learning sciences domain. But its translational nature also makes it useful in maximizing the preservation of core theoretical functions across media platforms. Translating from theory to an initial media platform is the starting point of translating from that platform to another. We present function mapping here in a case study of translation of theoretically-grounded functions across increasingly dissimilar media platforms.

The authors are designers and developers of an educational virtual environment, Scale Worlds, that requires virtual reality (VR) equipment to experience (Wu et al., 2022). Scale Worlds engages users with numeric representations, and allows them to apparently grow and shrink by powers of ten to gain an experiential sense of number, and to recognize the broad range of scale in the universe, especially at scales beyond everyday experience. To increase access to this experience, we are engaged in the development of a flat-screen, web-based version. In earlier efforts to create two VR versions of Scale Worlds (SW), one in a Cave Automatic Virtual Environment (CAVE) installation and the other on a head-mounted display (HMD), we created an initial set of theory-to-feature mappings using function mapping, and we have extended these mappings in developing the web-based prototype. These versions — SW-CAVE, SW-HMD, and SW-Web (Figure 2) — represent increasing availability to users, but at costs to functionality (e.g., immersion, degree of embodiment) that must be carefully mitigated.

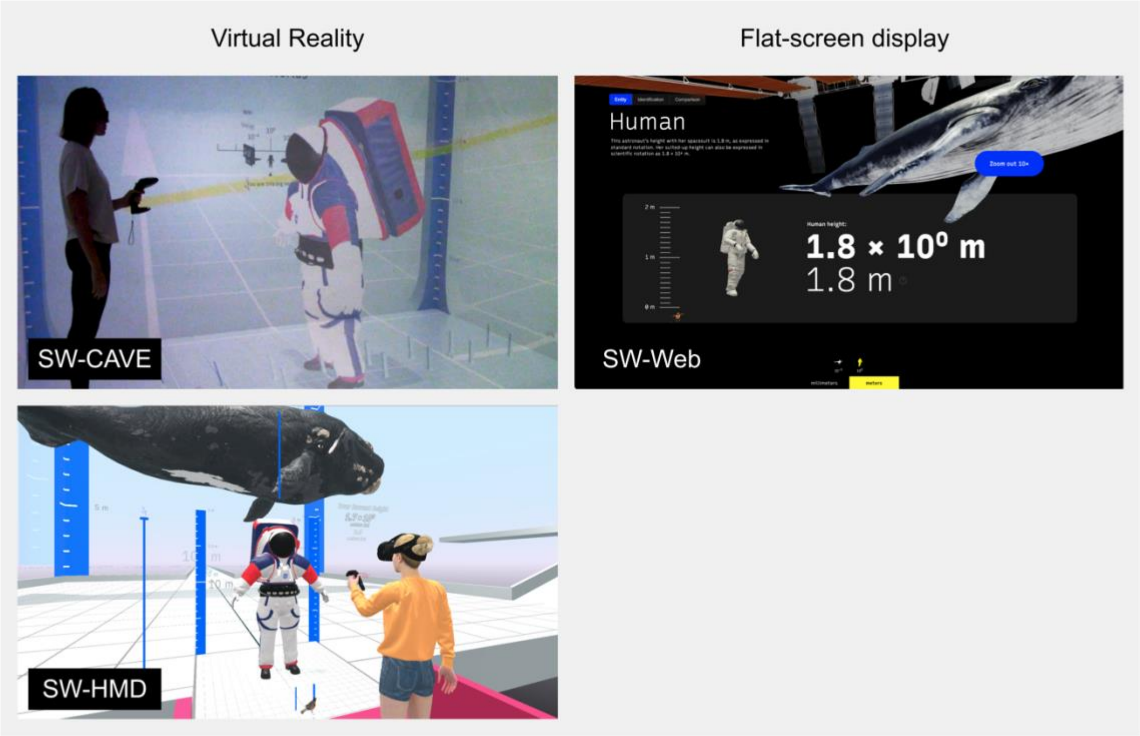

Figure 2. Scale Worlds running on three separate media platforms: SW-CAVE; SW-HMD; SW-Web.

Scale Worlds is central to a research project (DRL-2055680, National Science Foundation, USA) that addresses the Next Generation Science Standards' crosscutting concept of "scale, proportion, and quantity" (National Research Council, 2012), which is fundamental across STEM subjects and at all instructional levels. Scale cognition is required in working across sizes and scales, and a growing body of literature describes how scientists and students need to think to accomplish this (Delgado, 2013; Magana et al., 2012; Tretter et al., 2006a, 2006b). Magana et al. (2012) introduced five scale cognitive processes that build upon one another. We will describe these processes shortly in relation to features of Scale Worlds, but it is important to note that they characterize how people must think in order to successfully work with scale, with no direct guidance on how the processes might be mediated. This is why translation is necessary.

In the following section we use function mapping to track theoretical assertions — primarily from scale cognition theory — across versions of Scale Worlds. In a subsequent section we use the same function mapping exercise to compare SW-Web to Universcale (Nikon, n.d.), a precedent for Scale Worlds that was also developed for a flat-screen display. This comparison illustrates the systematic results of designing from established theoretical frameworks. Although we must speculate about Universcale's development, it is exceedingly unlikely that its developers employed a form of function mapping, and it appeared online no later than 2007, predating the scale cognition theoretical frameworks available to us (Delgado, 2009, 2013; Magana et al., 2012).

2 Translating functions across media platforms

Mori et al. (2004) proposed a "one model, many interfaces" approach in which designers create abstract descriptions of functionality that inform the user interface across multiple media platforms. For example, the authors describe designing a select museum section function: on a desktop they use a graphical map whereas on a phone, due to the smaller screen size, they use a list of names. Function mapping's translational nature differs from this approach in that it is specifically about mapping functionality derived from theory outside the design domain. Thus, designers are not themselves creating abstract descriptions of functionality. Rather, they are accounting for others' descriptions of desirable or necessary cognitive or affective functions (i.e., from non-design literature) that design features might ultimately facilitate. The Mori et al. (2004) publication establishes that designers seek to preserve functions across media platforms based on abstract underlying factors, and function mapping contributes to the literature by extending this concern back into the original derivation of the functions in question themselves.

To elucidate the full translation process from theory to function, and then like Mori et al. (2004) from media platform to media platform, we present the Scale Worlds project as a case study. Our goal is not to further scale cognition theory, but rather to further theory-driven and cross-media design. To that end, we have divided the accounting of our function mapping for Scale Worlds into two parts, based on the different subjective experiences of designing from isolated theoretical assertions (part I, multiple sources) and from a more organized theoretical framework (part II, Magana et al., 2012).

The function map for both parts is provided as Table 1. Columns track the three versions of Scale Worlds shown in Figure 2, and they are arranged left to right in the order in which they were developed in cross-media design: SW-CAVE first, SW-HMD second, and SW-Web third.

2.1 Case study, part I: Functions derived from isolated theoretical assertions

The following analysis is summarized in assertions A–E in Table 1. The assertions in question are "isolated" in the literature in the sense that they appear in prose format within extensive articles, and require some degree of insight to realize their relevance to multimedia design. But we consider such insights to be within the wheelhouse of designers.

2.1.1 Table 1, assertion A

Tretter et al. (2006a) is a seminal work in scale cognition theory, in which the authors quantitatively assessed the accuracy of conceptions of scale across a range of scientific expertise, and qualitatively characterized those conceptions. Scale is crucial across science and engineering disciplines, and so their findings are important for science and broader STEM education. Tretter et al. (2006a) found that scientists, when working at scales beyond everyday experience, imagine themselves traversing "scale-worlds": "To conceptually interact with scales far removed from human scale, experts used strategies of mentally jumping to a new scale-world" (p. 1061). These scale-worlds have distinguishing properties, important to the science disciplines, and thus students should ultimately be able to imagine and traverse scale-worlds. This is the fundamental concept of Scale Worlds, beginning with SW-CAVE, and for traversal Scale Worlds' main feature is a scaling animation, which animates elements to give the user the impression that they are growing and shrinking. This is based on our initial insight that, to promote expert science conceptualizations, such traversals should be egocentric, and thus the second, third, and fourth authors sought funding to develop a VR-based scale-worlds experience. The first author later led in development of SW-Web in part as his master's thesis project, thereby extending the Scale Worlds portfolio with a version that could not be egocentric, but could only be allocentric, i.e., with the user outside of the frame of reference. This experiential reduction is counterbalanced by the dramatically increased accessibility of a website over VR, which requires special equipment.

Table 1. Function mapping across three versions of Scale Worlds on distinct media platforms: functions derived from isolated assertions (A–E) and from a theoretical framework (F–J).[1]

	Design Specification		
Theoretical Assertion	**SW-CAVE**	**SW-HMD**	**SW-Web**
A. “Experts used strategies of **mentally jumping** to a new scale-world” (1 [p. 1061])	Scaling animation		
B. Abstract linkages between worlds and: mathematics (1); numeracy (2); embodiment (3); orientational conceptual metaphor (4); and mental models	Interactive navigation panel	Passive numeric panel	Numbers in bisecting plane
	Up-down gesture on exponent (3,4)	Up-down gesture with button (3,4)	Zooming concept conveyed verbally (mental model)
C. Link to human scale (1 [p. 1079])	Initial scale-world is Human World		
D. Size landmarks as “exemplars of a category” (5 [p. 307])	Entity presence and varying sizes		
E. Size landmark memory traces (1) and **numeracy** (2) for base-10 number system	Limited number of entities that are keyed pairwise to decimal places		
F. Generalization (6)	Multimodal experiential cues*		Visual cues*
	—		Number line grouping of entity icons by metric unit
G. Discrimination (6)	Entities ordered small to large		
H. Logical proportional reasoning (6) and **nested LPR** (7)	Fixed entity positions before and after scaling (6)		
	—		Ratio panel consistency (7)
I. Numerical proportional reasoning (6)	Forest of orientative posts keyed to CAVE dimensions	Teleportation	Comparison mode
	Stacking action		*
	—		Numeric ratios in ratio mode
J. Mathematical reasoning (6)	Rulers on posts	Standing rulers	Rulers on bisecting plane
	Metric grids		*

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[1] Sources: (1) Tretter et al., 2006a; (2) Weller et al., 2023; (3) Wilson, 2002; (4) Lakoff & Johnson, 1980; (5) Tretter et al., 2006b; (6) Magana et al., 2012; (7) Delgado & Peterson, 2018. Asterisks (*) indicate features that are planned, not implemented.

Assertion A is the very reason the Scale Worlds project was pursued. It led to the representation of different scale-worlds and traversal between them through the scaling animation — this can be viewed using hyperlinks 1–3 below. Other theoretical assertions determined what would appear within scale-worlds, and how the user would control traversal.

1. SW-CAVE: http://vimeo.com/849918899
2. SW-HMD: http://vimeo.com/851124234
3. SW-Web prototype: http://vimeo.com/849916157

2.1.2 Table 1, clustered assertions B

Tretter et al. (2006a) determined that scientists retained "abstract linkages" between scale-worlds and mathematics, which suggested that we key numeric representations directly to the worlds — which also generally serves the project goal of promoting numeracy (Weller et al., 2013). This assertion, like assertion A, appears in Tretter et al.'s (2006a) abstract, and thus it was not difficult to find. We specified abstract linkages in the form of: a navigation panel in SW-CAVE that users directly manipulate to initiate scaling, which displays the user's "current size" in both scientific and standard notation; a similar numeric panel in SW-HMD as a heads-up display (HUD) users can passively observe changing; and numeric representations for the current central entity in SW-Web's bisecting plane (Figure 3A, "numbers in bisecting plane"). In terms of cross-media design, we did not enable teleportation in the CAVE (see explanation below in assertion I), and the resulting limited space for movement enabled us to provide the interactive navigation panel in a fixed position. In SW-HMD, when we enabled teleportation, a fixed-position panel would largely be unavailable to users, and so we utilized the HUD to keep the crucial numbers in sight. But to make them interactive, we would have needed to increase the size to such a degree that visibility of the entities and other environmental features would be greatly reduced.

We also considered embodied cognition (Wilson, 2002), the theory that the physical body is inextricably linked to the mind, in providing abstract linkages to mathematics. Interaction with the navigation panel in SW-CAVE involves: pointing at the exponent in scientific notation and gesturing up or down to grow or shrink, respectively; and pointing at the decimal in standard notation and gesturing left or right to move the decimal by one place and thus shrink or grow, respectively. In SW-HMD, where the HUD replaces the interactive panel, a controller button is pressed to initiate scaling, but only when the user is pointing up or down to grow or shrink, respectively. The up-down swipes on the exponent in SW-CAVE and up-down pointing in SW-HMD both utilize an orientational conceptual metaphor association of up-is-more (Lakoff & Johnson, 1980). The left-right swipes on the decimal in SW-CAVE are simply meant to align with teachers' common instruction to "move the decimal." Embodied cognition is relevant in the VR versions of Scale Worlds, but in SW-Web, the allocentric user-to-media relationship suggested to us that gestures would not be impactful. We abandoned the target mental model of self-size scaling — i.e., the concept that it is the user who is growing and shrinking, not other elements in the environment — because the user could no longer be an element integrated into scale-worlds. Instead, embedded language suggests that what occurs during scaling animations is zooming in and zooming out, which is reminiscent of instrumentation such as the microscope or telescope.

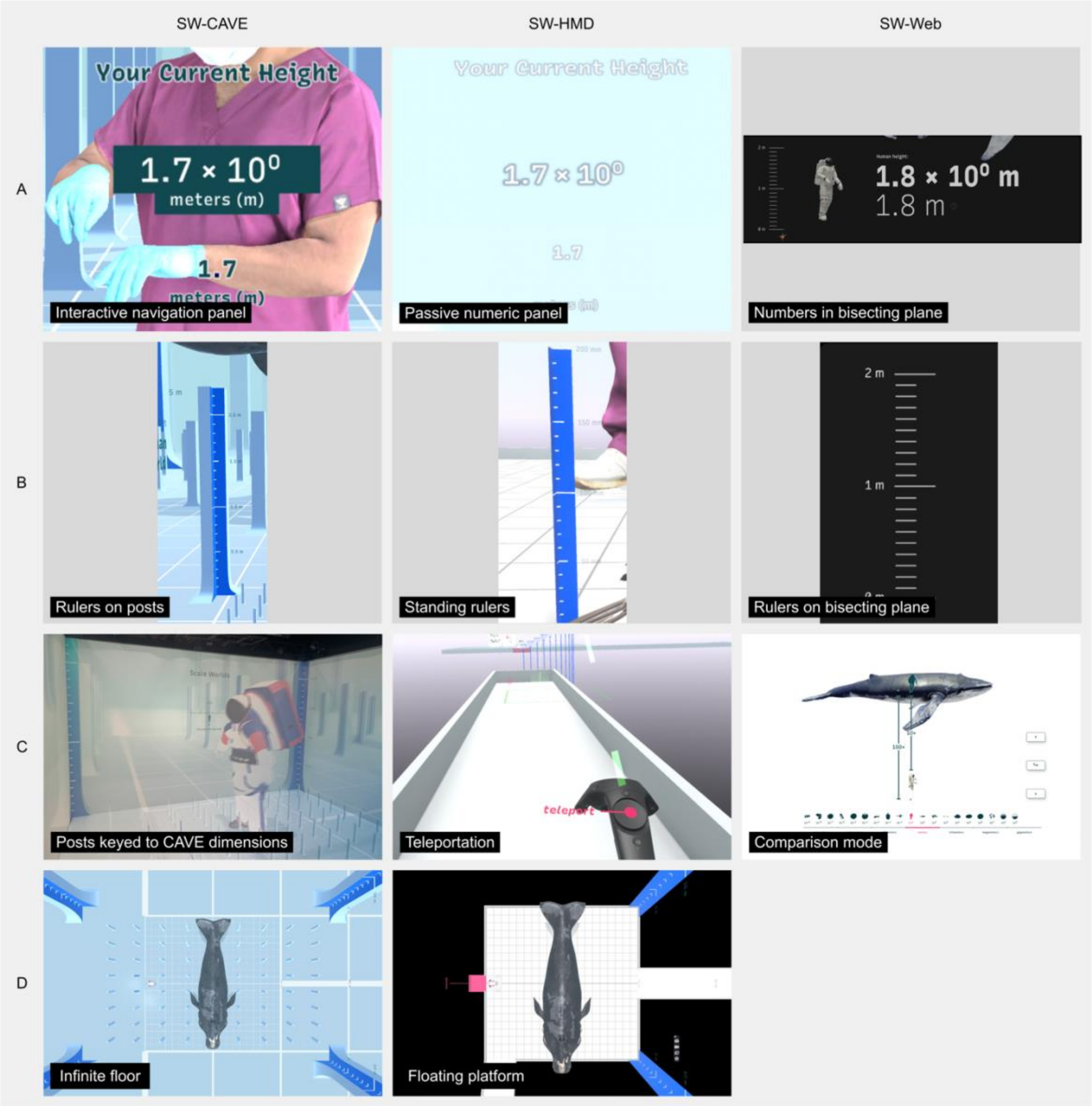

Figure 3. A selection of Scale World's features as realized on three separate media platforms: (A) CAVE; (B) HMD; (C) Web.

2.1.3 Table 1, assertion C

Following an interview of a nanoscale expert, Tretter et al. (2006a) emphasized the "importance of maintaining at least a tenuous link between the nanoscale and human-scale worlds" (p. 1079). From this, we specified that Scale Worlds would always load at Human World, thus linking the world of everyday experience to scale-worlds of the very large and very small through scaling animations. Unlike assertions A and B, this theoretical assertion was "buried" deeper in the article, but stood out to us because it described an experiential relationship that conformed to the traversal of scale-worlds we were already building into the environment.

2.1.4 Table 1, assertions D and E

We discuss assertions D and E together as an example of how theory-driven design can require synthesis across sources that vary in specificity. Tretter et al. (2006b) note that “people’s conceptions of scaling must… contain prototypes as exemplars of a category” (p. 285; a specific assertion D). Given our emphasis on numeracy (a more general “assertion” E), all versions of Scale Worlds present the user with one entity per power of ten. Tretter et al. (2006b) describe the utility of “size landmarks” as being “stable reference points” for forming mental models (p. 307), and by assigning a single entity per power of ten, Scale Worlds gives users entity reference points to individual decimal places in our base-10 number system (Weller et al., 2013) — an enriched mental model of number. We assume that too many entities would make remembering individual entities more difficult, thus destabilizing the frame of reference to number places.

2.2 Case study, part II: Functions derived from a theoretical framework

In contrast with assertions A–E, assertions F–J are drawn from a single theoretical framework, Magana et al.’s (2012) scale cognitive processes, which describe intellectual skills necessary to successfully engage with scale — a “scale-literacy.” The five scale cognitive processes represent increasing levels of sophistication, moving from size through scale, in the order we discuss them below and as seen in Table 1. These examples of cross-media translation are more complicated than those described above, and we reiterate the assertions from Table 1.

Table 1, assertions F and G reiterated.

	SW-CAVE	**SW-HMD**	**SW-Web**
F. Generalization (6)	Multimodal experiential cues*		Visual cues*
	—		Number line grouping of entity icons by metric unit
G. Discrimination (6)	Entities ordered small to large		

2.2.1 Table 1, assertions F and G

The first scale cognitive process is generalization, the ability to group things of related sizes, and the second is discrimination, the ability to order things serially according to size. Scale Worlds broadly facilitates these processes by giving users an experiential lexicon of scientific entities — which we introduced in assertions D and E — among which they can generalize and discriminate. More particularly for generalization, we plan to implement multimodal experiential cues within SW-CAVE and SW-HMD, or visual, audible, and haptic signifiers that change periodically between scale-worlds, helping users relate similar entities. For instance, the color scheme could switch to grayscale when the user shrinks smaller than the wavelength of visible light, and ambient buzzing sounds and a vibrating controller might accompany entities small enough to be subject to the uncertainty principle. In practice, VR users commit to an immersive experience when employing the technology, while users on a web browser are likely to be in a situation where haptic output is unavailable and sound is undesirable. Thus, we expect to incorporate only visual experiential cues in SW-Web. This means that, due to differences in media platform, the absence of nonvisual sensory stimuli in SW-Web renders that version weaker on generalization. To compensate for this, a number line at the bottom of the screen organizes groups of three scale-worlds into realms defined by the meter and its multiples (e.g., kilometer) and submultiples (e.g., millimeter), giving users an additional means of grouping entities.

2.2.2 Table 1, assertion H

The third scale cognitive process is logical proportional reasoning (LPR), which involves relating two similar size ratios. Magana et al. (2012) provide the example of the size difference between ant and human being similar to the size difference of the DNA double strand and a bacterium (p. 2187). This analogy can be expressed as:

ant : human :: DNA double strand : bacterium

LPR provides the paradigm of Scale Worlds, where the user seems to grow and shrink, witnessing reality from the perspective of the entities that represent scale-worlds (or in the case of SW-Web, the user zooms in and out through a viewport). At the end of each scaling animation, the entities have replaced one another in consistent fixed positions. In the user's memory, earlier entity arrangements are readily compared to current entity arrangements. And even within a single scale-world, the user experiences entities that vary in size by tenfold increments, permitting visual ratio comparisons such as acorn to human and robin to whale (which are equivalent at 1:100).

Table 1, assertion H reiterated.

	SW-CAVE	**SW-HMD**	**SW-Web**
H. Logical proportional reasoning (6) and **nested LPR** (7)	Fixed entity positions before and after scaling (6)		
	—		Ratio panel consistency (7)

SW-Web includes a ratio mode that facilitates LPR, compensating further for the lack of embodiment on its media platform (Figure 3). Along with an alternate camera view of the entities, the ratio mode utilizes entity icons, in a ratio panel, to explicitly relate entity sizes (Figure 3B). A central entity is flanked by two more entities, separated by colons (":"), and the flanking entities are at equal increments smaller and larger than the central entity (the "consistency" noted in Table 1). This exemplifies a special form of LPR that we have hypothesized, nested logical proportional reasoning (Delgado & Peterson, 2018), in which the two ratios share a central element. For instance, acorn is to human as human is to International Space Station, wherein the human is the shared element.

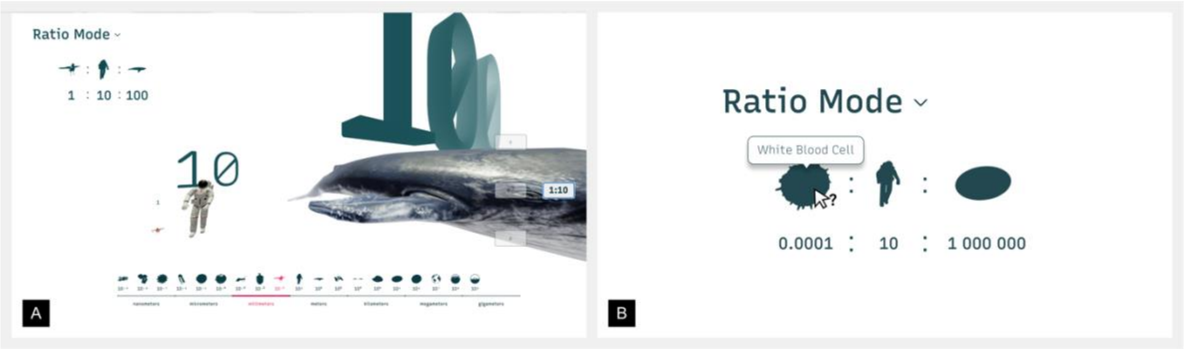

Figure 4. SW-Web ratio mode: (A) full view; (B) ratio panel. The user can select entities in ratio mode to reveal new ratios.

2.2.3 Table 1, assertion I

The fourth scale cognitive process is numerical proportional reasoning (NPR), “a process of measurement consisting of ‘assigning numbers to represent qualities’” (Magana et al., 2012, p. 2187, citing Campbell, 2005, p. 233). A forest of orientative posts (Figure 5A) was created for SW-CAVE to assist users in estimating the sizes of distant entities, due to limitations of the CAVE. There is no ceiling in this particular installation (Figure 5B), and thus anything visible to the user that is very large, and would thus require looking up, must be placed at a distance. Furthermore, this technological limitation in turn suggests an enforced limitation, that the user not be permitted to teleport — there would be no purpose in being proximate to something large that cannot be seen. The forest of orientative posts emerged in an attempt to facilitate NPR while overcoming these limitations.

Table 1, assertion I reiterated.

	SW-CAVE	SW-HMD	SW-Web
I. Numerical proportional reasoning (6)	Forest of orientative posts keyed to CAVE dimensions	Teleportation	Comparison mode
	Stacking action		*
	—		Numeric ratios in ratio mode

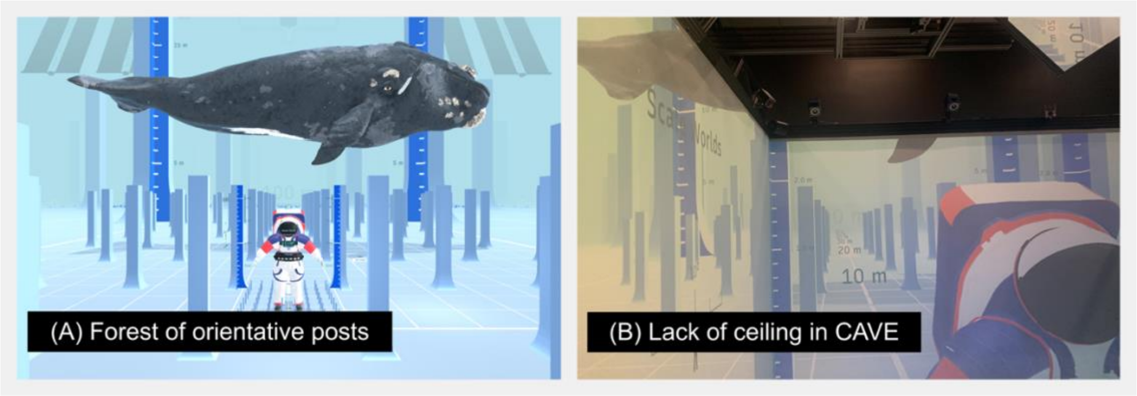

Figure 5. (A) Forest of orientative posts for SW-CAVE; (B) Lack of ceiling in CAVE.

The four posts nearest the user appear in the corners of the physical CAVE, reinforcing its dimensions. This is the space within which the user can move, and thus we expect them to have a natural embodied sense of the size of that space, directly related to their own sense of self-size. The forest is a pattern of the posts virtually extending away from the physical CAVE at the CAVE-size increment. This provides perspectival cues for the user to visually project the physical CAVE adjacent to large, distant entities. If the user employs these perspectival cues and feels like they are about a tenth the length of a distant right whale, then they are employing NPR. This is a form of unitization, wherein a shorthand unit of measure — in this case the CAVE, or nested within that the user’s own height — is utilized to measure something else (Lamon, 1994; Tretter et al., 2006a).

Following the primary development of SW-CAVE, the forest of orientative posts was initially implemented in SW-HMD. However, we quickly realized that the role of the posts was entirely dependent upon limitations particular to the CAVE as described above. Simply employing teleportation preserved this function (Figure 3C, “teleportation”): the user in SW-HMD can teleport themselves alongside and underneath large entities, thus facilitating the relative size comparisons (using self-size) that were more difficult in the CAVE. Permitting teleportation in turn led us to converting SW-CAVE’s seemingly infinite floor into a limited floating platform in SW-HMD (Figure 3D, “floating platform”), to keep the user within a reasonable area. Two bridges were added as beneficial vantage points beyond the main platform.

As in the CAVE-to-HMD translation, the subsequent HMD-to-Web translation required a reconsideration of the NPR function embodied in the orientative posts in SW-CAVE and the user’s ability to teleport in SW-HMD. In both cases, the features rely on the egocentric immersion of VR (e.g., emphasizing the user’s self-size to help them unitize), but the flat-screen display of the web does not allow for unitizing based on the user’s body. We developed a comparison mode for SW-Web (Figure 3C, “comparison mode”) that rotates the viewport such that the axis along which the entities are arranged is largely parallel to the picture plane of the user’s display. Due to the exponential arrangement of entities and limited screen space, this mode removes the current largest entity from view. But by reducing perspectival depth in relation to the entities, it becomes easier to compare their sizes. Furthermore, lines connect the visible entities, labels quantify the difference between them (at “10×” or “100×”), and icons of the smaller entities are placed over larger ones. The labels are a more passive but also more explicit means of facilitating NPR than the unitizing users can perform in SW-CAVE and SW-HMD, revealing how many times larger one entity is than another. The icons are a more active means of NPR, since the user can make a visual comparison themself.

Additional facilitation of NPR includes a stacking action, in which a smaller entity is repeated next to a larger entity to visually express unitization (e.g., an acorn is stacked next to a bird). The entities (as size landmarks) only roughly differ from one another in linear measure by powers of ten, and many stacking pairs occur in increments such as nine antibodies approximating the width of Coronavirus. This may help emphasize to users that powers of ten, especially as represented in scientific notation (e.g., “1.7 × 108,” equal to 170 000 000), are handy for estimations of dramatic differences in size.

Finally, the ratio panel in SW-Web compensates for NPR as it did for LPR, in that it explicitly quantifies the current ratios between two displayed entities (e.g., “1:100”; Figure 4).

2.2.4 Table 1, assertion J

Table 1. assertion J reiterated.

	SW-CAVE	SW-HMD	SW-Web
J. Mathematical reasoning (6)	Rulers on posts	Standing rulers	Rulers on bisecting plane
	Metric grids		*

The fifth and final scale cognitive process is mathematical reasoning (MR), or “the assignment of an absolute number or measurement to an object” (Magana et al., 2012, p. 2187). MR is in part facilitated by metric grids in all Scale Worlds versions, which include explicit measurements (though these are not yet implemented in SW-Web). More instructive for our purposes are rulers derived from the orientative posts in SW-CAVE, of which there are actually two types. All of the posts, as described above, facilitate NPR. But the posts that are positioned at the physical CAVE's corners have inset corners that map to the physical CAVE's walls, upon which rulers are inscribed. As the user visits scale-worlds, the ruler measurements are updated numerically, facilitating MR. For instance, if the user grows in SW-CAVE three times starting at Human World, they will be in Brooklyn Bridge World, with post ruler labels reflecting 0.5 km, 1.0 km, 1.5 km, and 2.0 km. Though SW-HMD does not have the orientative posts infrastructure, we repeated the ruler facet of SW-CAVE's posts in SW-HMD as standing rulers. For SW-Web, we utilized the infrastructure of a bisecting plane, parallel to the plane of the viewport, to place rulers adjacent to entities (Figure 3A, "rulers on bisecting plane"). The bisecting plane not only situates the rulers, it also highlights one entity that represents the current power of ten the user is viewing. Thus in relation to design specifications beginning with the forest of orientative posts, function mapping helped us recognize that the NPR function required substantial theory-to-feature translations across media platforms, while the MR function required only minimal adjustments to a ruler's formal characteristics. Function mapping helped us focus on the theoretical justification for design decisions without being fixated upon platform-derivative design specifications.

The above examples are evidence of our use of function mapping to achieve a theoretical form of equivalency across dissimilar media platforms. We expect that this theoretical equivalency is at odds with a folk concept of equivalency that favors visual similarity. Retaining the orientative posts from SW-CAVE in SW-Web would be a superficial form of equivalency. It would make SW-Web look more like SW-CAVE, but we believe that our function mapping reveals that SW-Web is functionally more like SW-CAVE.

3 Design specifications with and without function mapping

We studied existing scale-related educational multimedia in advance of Scale Worlds development, including the Eames' Powers of Ten film (Eames et al., 1978) and two interactive websites, Scale of the Universe 2 (Huang, n.d.) and Universcale (Nikon, n.d.). Most similar SW-Web is Universcale (Figure 6). Though its current version carries a 2018 copyright, a Flash version that was not noticeably different appeared on the internet no later than 2007 — we conceived of function mapping beginning in 2021, and Universcale's developers probably did not employ anything like it. Furthermore, Magana et al.'s (2012) scale cognition framework, which guided much of the decision making evident in Table 1, was not yet published when Universcale was released.

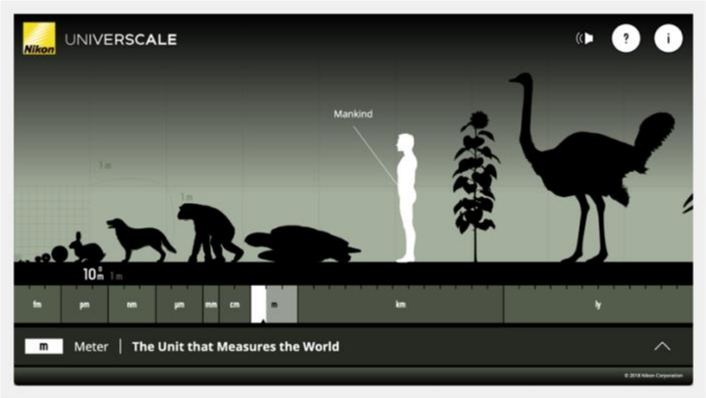

Figure 6. Universcale main view.

We now use function mapping to analyze Universcale's features according to the target functions of Scale Worlds, to better distinguish the outcomes of function mapping when, as with SW-Web, it is incorporated into design and development. A limitation of this approach is that we can describe SW-Web with authority, being its developers, while we can only speculate on Universcale, focusing on our interpretation of its features without knowledge of their development. The resulting function map is provided as Table 2, and we repeat the subdivision of Section 2 here, with isolated theoretical assertions preceding those from Magana et al.'s (2012) framework.

Table 2. Function mapping comparison of SW-Web and Universcale (Nikon, n.d.): functions derived from isolated assertions (A–E) and from a theoretical framework (F–J).[2]

	Design Specification	
Theoretical Assertion	**SW-Web**	**Universcale**
A. "Experts used strategies of **mentally jumping** to a new scale-world" (1 [p. 1061])	Scaling animation	
B. Abstract linkages between worlds and: mathematics (1); numeracy (2); embodiment (3); orientational conceptual metaphor (4); and mental models	Numbers in bisecting plane	Numbers in entity view mode
	Zooming concept conveyed verbally (mental model)	—
C. Link to human scale (1 [p. 1079])	Initially loads on the human	
D. Size landmarks as "exemplars of a category" (5 [p. 307])	Entity presence and varying sizes	
E. Size landmark memory traces (1) and **numeracy** (2) for base-10 number system	Limited number of entities that are keyed pairwise to decimal places	As many familiar and useful entities as can fit in the interface
F. Generalization (6)	Visual experiential cues*	—
	Number line grouping of entity icons by metric unit	Number line grouping units in variable-sized ranges according to common practices
	—	Poetic grouping subtitles
G. Discrimination (6)	Entities ordered small to large	
H. Logical proportional reasoning (6) and **nested LPR** (7)	Fixed entity positions before and after scaling (6)	Navigation using smaller and larger entities in entity view, in fixed positions (but in inconsistent increments)
	Ratio panel consistency (7)	Inconsistent ratios in entity view

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[2] Sources: (1) Tretter et al., 2006a; (2) Weller et al., 2023; (3) Wilson, 2002; (4) Lakoff & Johnson, 1980; (5) Tretter et al., 2006b; (6) Magana et al., 2012; (7) Delgado & Peterson, 2018. Asterisks (*) indicate features that are planned, not implemented.

I. Numerical proportional reasoning (6)	Comparison mode	—
	Stacking action*	
	Numeric ratios in ratio mode	
J. Mathematical reasoning (6)	Rulers on bisecting plane	Rulers in entity view
	Metric grids*	

3.1 Intraplatform comparison, part I: Functions derived from isolated theoretical assertions

Universcale features a number line that includes the meter, the kilometer, the light year (ly), and submultiples from the femtometer (fm) to the centimeter. An arrangement of silhouetted entities appears above the number line. Clicking on an entity pops up an entity view with a full-color version of the entity and didactic information (Figure 7). In the main view, a default animation slowly decreases scale in the absence of user input, with entities moving to the right as they increase in size. If the user clicks on a segment of the number line, a rapid animation reflects the scale change. If the user lets the slow animation continue to the proton at roughly 1 fm, a rapid animation will scale up to the universe, sized at 13.8 billion ly, and the default animation will resume. Introductory language that appears in a loading sequence suggests that, unsurprisingly, Universcale's developers shared some of our interests. For instance, "We use objects visible to the naked eye as yardsticks to identify those things invisible," calls to mind Tretter et al.'s (2006b) size landmarks. And, "By comparing and ranking these entities, we are able to accurately identify their true forms," reflects Magana et al.'s (2012) scale cognitive process of discrimination. But beyond these hints, we are left to speculate.

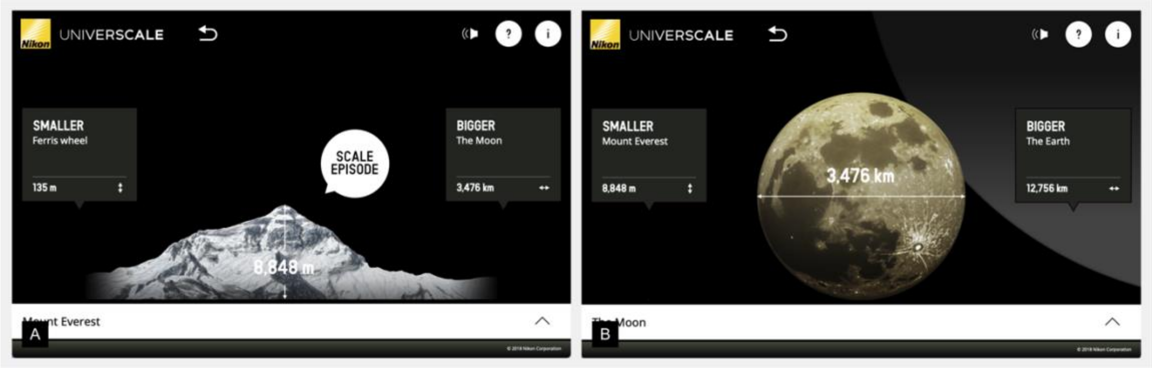

Figure 7. Universcale entity view: (A) Mt. Everest; (B) Moon.

All versions of Scale Worlds include one entity per power of ten with the expectation that fewer entities will be easier to recall than more entities, and to key exactly one entity to each power of ten both as size landmarks for decimal places, and to promote numeracy for our base-10 number system (Weller et al., 2013). Universcale utilizes powers of ten, most notably in its bracketing on the number line, but not to determine entity count — it includes a surfeit of entities at inconsistent increments. The space between 1 m and 10 m is occupied by eight partial or full entities: part of a rabbit (at the border), a dog, a chimpanzee, a turtle, a man, a sunflower stalk, an ostrich, and part of an elephant (crossing the other border). The space between 10 m and 100 m includes five entities: the remainder of the elephant, a "double deck bus," a giraffe, the Sphinx of Giza, and the tip of a whale. In contrast, the space between 100 km and 1000 km is empty (Mount Everest is the last entity of the previous range, and the Moon is the first entity of the next). The sphinx and bus are wide, leaving little room for other entities, which is likely why only five entities appear in that range compared with the eight entities in the 1–10 m range, and we infer a criterion for entity selection that all desirable entities that could fit within a given space were included. We have had difficulty identifying entities for Scale Worlds around the size range of the empty 100–1000 km in Universcale, and have carefully selected entities that, when possible, are familiar to users, or that are otherwise useful in science education (Gampp et al., 2022). But because we key entities to decimal places, we would only leave an entity slot empty if there were truly nothing in the universe near the respective size (as is the case at multiple powers of ten in the subatomic range). Due to this, we have iteratively added and replaced various solar system bodies that we affectionately call "space potatoes," which are neither distinct as shapes, nor familiar to the average student — e.g., SW-Web currently includes Eros (an asteroid) and Haumea (a dwarf planet).

These considerations are summarized in Table 2, assertions A–E, as similarities among and differences between SW-Web and Universcale, and they exemplify our principled approach for Scale Worlds according to an agenda that is surely distinct from the agenda that Universcale was developed to serve.

3.2 Intraplatform comparison, part II: Functions derived from a theoretical framework

We now return to Magana et al.'s (2012) five scale cognitive processes, and the following analysis is summarized in assertions F–J in Table 2.

3.2.1 Table 2, assertion F

SW-Web addresses generalization through visual experiential cues (which are planned but not yet implemented) and a number line that groups scale-worlds in threes, according to the meter and its multiples and submultiples. Universcale has no feature equivalent to the cues, but it does group entities within its respective number line. Due to our emphasis in Scale Worlds on the overall pattern of three decimal places in the metric system, and the convention of spaces separating groups of three digits in long numbers (e.g., 0.000 000 000 000 000 01), SW-Web utilizes only the large-increment multiples and submultiples of the meter (e.g., it excludes the centimeter). In contrast, Universcale subdivides its number line in a manner more consistent with how units are used in practice by scientists. The centimeter is used for two powers of ten, the kilometer for 13 powers of ten, and the light year for 12 powers of ten. Again, differing agendas are apparent. We expect that Universcale is more entertaining in its presentation of entities — including its poetic subtitles for entity ranges, such as "the Great Primordial" for the femtometer range, "Limits of the Naked Eye" for the 1–10 mm range, and "Realm of the Palm" for 1–100 cm — while SW-Web creates stronger dual-coded associative memory traces (Sadoski & Paivio, 2013) that cognitively bind entities and numbers.

3.2.2 Table 2, assertion G

SW-Web and Universcale both address discrimination through a serial ordering of entities, and both maintain Tretter et al.'s (2006a) "tenuous link" to the human scale, with the human as a starting point. Universcale utilizes two-dimensional (2D) black silhouettes rather than full-color entity pictures in its main view, though full-color entities are available when clicking on an entity silhouette. In contrast, SW-Web utilizes full-color 3D entities. SW-Web's 3D environment's affordances in turn permitted us to easily create the alternate viewing modes that were ultimately critical in addressing various theoretical assertions. The Universcale silhouettes may serve as better tools for making visual size comparisons because the lack of distracting qualitative detail better emphasizes quantitative differences (Peterson, 2022, p. 9). But it is likely that the developers of Universcale chose black silhouettes due to performance issues, dramatically reducing the processing power needed to smoothly animate the entities.

3.2.3 Table 2, assertion H

SW-Web addresses logical proportional reasoning (LPR) by arranging entities in consistent positions such that entities removed from others by powers of ten replace them at the culmination of scaling animations. Universcale continuously animates entities at a slow pace, or upon a user clicking on the number line at a very fast pace, and there are no distinct positions into which entities are placed. This does not promote ratio comparisons. SW-Web’s ratio panel additionally isolates three entities in two equivalent ratios. Universcale’s entity view similarly presents a central entity with one smaller and one larger entity beside it. However, the ratios are not always equivalent to one another, especially due to the inconsistent increment of entities. For instance, the Moon view includes a 1:400 ratio of Mount Everest to Moon, and a 1:4 ratio of Moon to Earth (Figure 7B). The ratios do not consistently support LPR. However, this entity view permits the user to navigate with the smaller and larger entities, which may reflect back on SW-Web’s use of fixed entity positions. But Universcale’s version is somewhat muted in the sense that it is in a pop-up separate from the main view, and because the ratio increments are inconsistent. It is at least occasionally an example of LPR.

3.2.4 Table 2, assertion I

SW-Web addresses numerical proportional reasoning (NPR) through the comparison mode (Figure 3C, “comparison mode”), the stacking action, and the ratio mode’s numerically represented ratios. There is no evidence of an NPR function in Universcale. For users to unitize one entity to estimate the size of another, they would need to compare entities on opposite sides of the screen that are separated by other entities.

3.2.5 Table 2, assertion J

SW-Web addresses mathematical reasoning through the bisecting plane’s ruler in entity mode, and metric grids (which are not yet fully implemented). Universcale also has metric grids, but only occasionally do entities overlap finer inscribed grids to permit more accurate estimations of size. Both SW-Web and Universcale explicitly provide entity lengths in their respective entity views; SW-Web does so in its default entity mode in scientific and standard notation, while Universcale requires the user to click an entity, which pops up the entity view containing an accurate measurement.

Our analysis suggests that although Universcale is a deeply engaging and sophisticated environment, it does not address the full battery of scale cognitive processes: NPR is apparently not facilitated, while LPR’s facilitation is minimal. While it is unfair to expect Universcale to facilitate scale cognitive processes that were not on the developers’ agenda, the omissions demonstrate that it takes a deliberate approach to facilitate all of these processes. Function mapping’s careful tracking of theoretical assertions through the design specifications for distinct features can focus designers’ attention on factors that relevant literature suggests they should care about.

4 Conclusion

Scale Worlds was initially conceived as a VR experience. But teachers and students will not always have VR resources, and web-based resources like Universcale and SW-Web can bring scale cognitive experiences to education at a large scale. Function mapping subdivides multimedia into distinct design features, permitting analysis at a granular level. Researchers studying scale cognition could use function maps of SW-Web to assess its impact according to specific scale cognitive processes. Teachers in a district that has adopted scale cognition in unit learning objectives could use function maps to determine which features of SW-Web to draw students' attention to at any given time, as a pedagogical strategy. In such a school district, where Magana et al.'s (2012) scale cognitive processes have been adopted, SW-Web would be preferable to Universcale, though in other situations valuation may well reverse.

Through function mapping, we made deliberate design decisions to preserve core aspects of functionality across three media platforms. The function mapping process revealed gaps in functionality, which we were able to address formatively. For instance, we realized that SW-Web lacked an intentional feature supporting NPR (as does Universcale, according to our analysis). SW-Web's entity mode required the user to initiate the scaling animation to see entity measurements in the bisecting plane one at a time, and to hold one measurement in memory while the other was visibly present. This was limiting. Function mapping suggested a solution, which took the form of the comparison mode, permitting more direct numeric size comparisons.

We have shown that function mapping is beneficial to designers who are working across media platforms and have a theoretical agenda beyond standard concerns, such as usability. By stepping back and analyzing features according to theoretically motivated functionality, designers can ensure that chosen functions are embodied in media. Function mapping reveals gaps in design specifications and can call attention to superfluous features. Through function mapping, designers can ensure that design features address the affordances and limitations of media platforms; and others (e.g., teachers) can use function maps to make informed decisions on the selection of media among alternatives.

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