Examining Narrative Sonification: Using First-Person Retrospection Methods to Translate Radio Production to Interaction Design

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We present a first-person, retrospective exploration of two radio sonification pieces that employ narrative scaffolding to teach audiences how to listen to data. To decelerate and articulate design processes that occurred at the rapid pace of radio production, the sound designer and producer wrote retrospective design accounts. We then revisited the radio pieces through principles drawn from guidance design, data storytelling, visualization literacy, and sound studies. Finally, we speculated how these principles might be applied through interactive, voice-based technologies. First-person methods enabled us to access the implicit knowledge embedded in radio production and translate it to technologies of interest to the human–computer-interaction community, such as voice user interfaces that rely on auditory display. Traditionally, sonification practitioners have focused more on generating sounds than on teaching people how to listen; our process, however, treated sound and narrative as a holistic, sonic-narrative experience. Our first-person retrospection illuminated the role of narrative in designing to support people as they learn to listen to data.

CCS Concepts: • **Human-centered computing** → **Interaction design process and methods**; **Auditory feedback;**

Additional Key Words and Phrases: Retrospection, sonification, radio, sound, narrative, data, interaction design, voice user interfaces

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1 INTRODUCTION

As the COVID-19 outbreak grew into a global pandemic that disrupted our lives and ignited financial turmoil, the first author of this article, Jordan Wirfs-Brock, found herself unable to do much

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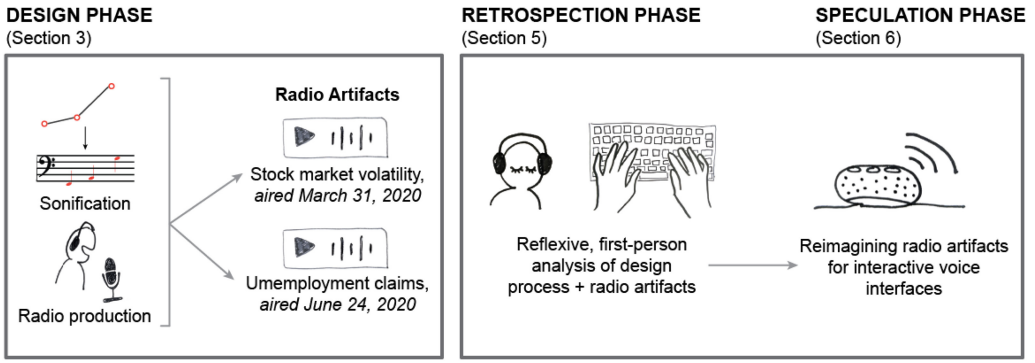

Fig. 1. This diagram shows the main stages of our process, mapped to sections within this article. We began by designing narrative sonification pieces for the radio (described in Section 3). Next, we reflected on the process of creating those radio artifacts (findings in Section 5) and speculated how we might reconceptualize our radio artifacts as voice user interface interactions (findings in Section 6).

else other than consume news. She had trouble focusing on work—reading was hard and writing was even harder. So she turned to a small act of making: translating the data of the volatile stock market into sounds. She created a *sonification* of the daily closing price and daily percent change of the Dow Jones Industrial Average—in part, to just do *something*, and in part to make sense of the chaotic world. This sonification, which she described in a video and posted on Twitter, eventually made its way to Kai Ryssdal, host of *Marketplace*, a daily U.S. radio programme that seeks to help its 14 million listeners understand the complex economic forces that impact their lives. Ryssdal asked Alli Fam, the second author of this article and a producer at *Marketplace*, to reach out to Wirfs-Brock and adapt the sonification for the radio programme. Fam and Wirfs-Brock then collaborated to turn the stock market sonification in a radio piece. Months later, Fam and Wirfs-Brock collaborated on another sonification for *Marketplace* about unemployment claims.

As we collectively reflected on these events, we identified a research through design approach [77, 90] as a fitting method for exploring the role of *narrative storytelling* in sonification and sound-based interaction design (outlined in Figure 1). To understand what made our radio sonification artifacts compelling and effective, we examined our own design processes using *first-person retrospection*, which centers how we make sense of the world by telling stories about our experiences. Through close listening, we also examined the radio artifacts themselves to understand the role narrative, delivered via radio interviews, played in supporting people as they learn to listen to data. By understanding these radio artifacts and our processes for creating them, we seek to translate implicit knowledge from radio's tradition of audio storytelling to the **human–computer-interaction** (**HCI**) domain of voice user interface design.

Sonification—conveying data through sounds [2]—is an active research area that has been around for decades. Yet while some examples are familiar—Geiger counters, alarms and notifications in cars, the crumpling paper trashcan sound for Macintosh computers [37]—sonification has not achieved the widespread appeal visualization has within data-driven cultures [44, 54]. Sonification practitioners have focused more on the generation of sounds from datasets than on teaching people how to listen to and interpret them. Humans are constantly interpreting meaning from sound: While walking on the side of a road, you might hear a car coming behind you and know exactly when to move over; or perhaps you can tell exactly who walked through the door because you recognize the sound of their footsteps. But we do not tend to do this as a conscious act, and we do not often do it with abstract data. We can develop these skills, which sound studies scholars

refer to as *analytic listening* [11], with time and effort. How might we better support people as they learn to listen to data analytically?

It is easy to forget that we had to learn how to swipe a touch screen, to send a tweet, or to read a bar chart. With sonification, because it is novel to many of us, that process of learning is present and emergent. As a sound designer and a radio producer, Wirfs-Brock and Fam had to learn to listen to data and then transfer that learning to the *Marketplace* audience. Our radio sonification pieces had an explicit goal of training the listeners' ears: We scaffolded the learning process with a narrative interview format that broke the sonifications down into smaller parts and then built them back up again so listeners could return to them with fresh ears.

First-person retrospective methods enabled us to access the implicit knowledge embedded in our radio production and sound design practices in order to translate them to the HCI community. After the radio pieces aired, we wrote retrospective *design accounts*. These written accounts reflexively decelerate and articulate our design processes, which occurred at the rapid pace of radio production. We re-listened to the radio artifacts, creating annotated transcripts and schematic diagrams of them to understand their structure. We also applied a *post hoc* theoretical lens to consider how design principles drawn from adjacent fields—guidance design, data-driven storytelling, data visualization literacy, and sound studies—were present or absent in our radio artifacts. Finally, we speculated how we might deliberately apply these principles to rethink our radio artifacts as interactive sonifications using emerging voice user interface technologies.

Through our process of first-person retrospection, we ask:

- How might we, as designers, use narrative storytelling techniques to support audiences in the process of learning to listen to data?
- What can HCI, and voice user interface designers specifically, learn from the seemingly non-interactive medium of radio?
- How can we use retrospection as a method to support interaction design?

Traditionally, sonification practitioners have focused on the design of *sounds*. Our work foregrounds the design of *experiences* by considering narrative scaffolds, sound design, and interactivity in concert to make sonification more accessible to general audiences. We contribute findings on how we might use temporality to make space for narrative, how we might establish shared linguistic and sonic vocabularies, how radio producers conjure proxy audiences in their minds, and how we can approach listening as a multi-layered experience. We also reflect on how interaction designers might relate to proxy users, how we can use narrative as a boundary object, and how retrospection can support sensemaking through intentional sparseness. By reflecting on our own design process, we identified how a holistic approach to designing narratives and sounds together can make sonification more accessible for general audiences as voice user interfaces become more powerful and pervasive.

2 RELATED WORK

To situate our work, we first discuss the specific genres to which our radio artifacts belong: sonification and explanatory journalism. Then, we touch on how the data visualization community has explored the role of narrative storytelling. Finally, we trace traditions of first-person retrospection and reflection in HCI and interaction design.

2.1 Sonification: Refocusing from Sounds to Learning

Data sonification is the practice of using sounds, particularly non-speech sounds [25], to convey data and information [2]. It is a subset of the broader field of *auditory display*, which also includes signals like alarms and auditory icons. As a research community, sonification practitioners struggle

with how to make themselves relevant to broad audiences, as evidenced by the perennial search for sonification's "killer app" [56, 80]. We suggest that some reasons sonification has failed to reach broad audiences are the tension between cognitive versus ecological approaches to sound design [65], a lack of emphasis on learning and training [2], and little focus on integrating speech with non-speech sounds [51].

One of the most widely used approaches to data sonification is *parameter mapping* [2], which involves converting a dimension of data into a dimension of sound to create an auditory graph (for example, mapping the Case-Shiller home index prices onto pitch [39]). Sonification practitioners often use multiple channels simultaneously—i.e., pitch conveys one data dimension and timbre conveys another—reflecting a "cognitive approach" to sonification that treats the brain as a computer that decodes the data behind sonic signals. This approach can be effective in communicating data [55]. It is also an easy entryway into sonification for practitioners [55], and has been adopted in public-facing, novice-oriented tools such as TwoTone.io.[1] In our own practice, Wirfs-Brock has used parameter mapping in the past because it is easy to explain to general audiences [86]. We employ it in our *Marketplace* sonifications as well. Yet some practitioners argue that a cognitive approach is reductionist [56, 65, 87]. Treating the brain as a computer that decodes sounds does not account for how people actually listen: People do not hear pitch, timbre, and tempo—they hear holistic sounds. Gaver incorporated this idea through an ecological approach to auditory icon design [35], creating the trashcan sound for Macintosh computers. His stance was that people hear the world, not the sound [36]. Recent embodied approaches to sonification [65, 66] pick up this thread by considering how conceptual metaphors and lived experiences contribute to how someone makes sense of sounds. Research into how the brain perceives sound provides evidence to support this approach [12, 38], and recent work on how people perceive soundscapes has explored the processes by which people turn incomprehensible sounds into meaningful stories by creating and refining mental models [28]. In these mental models, often "the distinction between sound and noise is essentially an emotional one" [24]. These ideas of ecological, metaphorical, and embodied meaning in sonification are conceptually promising, and we engage them in our own design practice. However, we have also found them challenging to implement. It is difficult to account for the individual lived experiences and associations each unique listener brings to the act of listening [66].

Whether sonification practitioners take a cognitive or an ecological approach, they are creating novel sounds and sonic contexts, thus listeners will need training in order to interpret them [2]. In a lab setting, training has been shown to help people understand sonifications [51], especially practice with reinforcement feedback [85]. Yet open questions remain: Do cognitive and ecological approaches require different types of training? And how might training be facilitated outside of a lab setting? We are inspired by Lenzi and Ciuccarelli's recent work on intentionality in advocacy-oriented sonifications [50], which turns a much-needed ear towards the challenges of reaching general audiences. This work, however, focuses on how narrative intent is conveyed through sound design, and not the framing narrative context in which the sounds are delivered.

Traditionally, the sonification community has largely ignored speech-based sounds, with the notable exception of work on *spearcons*, which are rapid iconized speech [26]. We are encouraged by recent research that shifts the focus towards understanding speech and non-speech sounds together: for example, Li and Walker's work on communicating health metrics through mixed-speech displays [51]; Lutz et al.'s development of an ambient sonification system that communicates web cookies through soundscapes and whispers [52]; and Smith and Moore's framework for verbal description to support non-speech sounds in physics simulations [76]. However, these works treat speech sounds as part of a sonification and do not consider the role

[1] https://twotone.io/about/.

of narrative scaffolding and exposition. Our work moves into this gap by holistically considering both non-speech sounds and spoken narrative framing, which we examine in the context of artifacts we created for broadcast radio.

2.2 Narrative Visualization and the Tension between Explanation and Exploration

Although narrative storytelling in sonification is under-researched, the visualization community has explored the role of storytelling in visual representations. The term we chose to describe our radio artifacts, *narrative sonification*, is a nod to *narrative visualization*, a subset of visualizations "intended to convey stories" [75]. Through surveying examples of data journalism, Segel and Heer identified common narrative forms such as annotated charts, animation and video [4], slide shows, and data comics [5]—and by naming these, drew research interest to them.[2] Narrative visualization is well suited to tell the story of how data-driven insight came to be, because it can, "communicate discoveries more successfully by reproducing something of the experience of finding them" [27]. Crucially, Segel and Heer noted a tension in narrative visualization forms between author-driven explanation and reader-driven exploration (or, as might apply to radio, listener-driven exploration). This raises questions about who is, and who should be, in charge of finding insight in data [64].

Radio presents unique challenges and opportunities for conveying the experience of finding insight in data: As a linear medium that progresses in one direction (forward), radio might be best suited for author-driven explanation, as is video [75]. However, in our first-person work, we examine the ways that radio, despite being linear and ephemeral, can actually be quite interactive in our minds. We also explore how narrative sonification can facilitate exploratory listener-driven formats in concert with emerging voice user interface technologies.

2.3 Explanatory Journalism in Service of "Civic Clarity"

The interplay of explanation and exploration is evident in *explanatory journalism and reporting*, which often employs narrative visualization techniques, using author-driven explanation as a springboard to encourage audiences to explore data visualizations on their own [82]. Explanatory journalism—observed in popular outlets such as *Vox* and the *New York Times*' "The Upshot" [45]—delivers context that can help audiences make sense of complex issues. In contrast with breaking news, which favours "speed over nuance" [45], the goal of explanatory journalism is "civic clarity" [21]. Explanatory reporting plays a critical role in a functioning democracy by contributing to an informed, engaged public [32, 45]. Journalist and writing coach Clark encourages practitioners to "slow down the pace of information," "introduce new characters or difficult concepts one at a time," "recognize the value of repetition," "use [apt] analogies," "develop a chronology," "reward the reader," and "announce difficult concepts" [21]. In our work, we employ many of these principles.

Historian Kathy Forde argues that the qualities people seek in news reporting reflect broader epistemological values: Whereas the "inverted pyramid" style of conventional news reports "reflected society's widespread faith in realism and the authority of facts," explanatory reports reflect a desire for "interpretation of complex events and phenomena placed in social, political, or cultural context" [32]. A renewed hunger for explanatory journalism has emerged during the COVID-19 pandemic: Clark claimed we are in a "potential golden age of explanatory journalism" as experts in health, science, and business contribute explanatory reports about the current crisis [21].

Explanatory journalism has long been a testing ground for new technologies, such as interactive simulation games [88]. *Marketplace*'s mission to help listeners understand the economic forces that touch their lives fits into this vein. The radio show has long used unconventional explanatory forms, such as playing musical riffs to represent the daily stock market performance [1]. In our

[2]In this and future work, we aspire to do the same for narrative sonification.

radio artifacts, we use familiar explanatory techniques and also explore how emerging techniques for presenting information—such as sonification—can aid engagement around data to support understanding.

2.4 First-Person Retrospection as Reflection on Interaction in HCI

Retrospection is the act of looking back, of contemplating the past. HCI researchers have used retrospection to understand user needs [68] through a range of techniques: calendars and timelines as memory aides [10, 33, 40, 41]; exercises that engage visual rather than verbal thinking, like self-portraits, conceptual diagrams, and sketch maps [6]; and examining digital traces such as Facebook posts [72] or Wikipedia edits [29]. Interaction designers have used retrospection as a first-person method to understand their practices—although often this method is present without being explicitly labelled as such [60, 89]. Retrospection is implicit in the act of documenting research-through-design work by writing academic papers; annotated portfolios as a sub-genre highlight such acts of retrospection as a way to develop design theory [8, 15, 43].

As Jordan and Henderson write in their work on interaction analysis, through retrospection, "the events themselves have disappeared; what passes as data is actually their reconstruction" [48]. We must be attentive to what we can access through retrospection and what remains inaccessible. Retrospection is not a complete (or even "accurate" [22]) account of the past—but that does not mean it has no value to researchers and designers [9]. Retrospection is a lens for viewing how we perceive past events—how we make sense of them, and how we tell stories about them. It is particularly useful for understanding narratives, which transfer knowledge between people and across time. For example, in *Talking About Machines* [61], Orr focuses on the retrospective stories copy-machine technicians tell each other in order to diagnose problems: "...stories are commonly used to make sense out of ambiguous situations or to represent sense-making in earlier events" [61]. In our work, we use first-person retrospection to unearth the knowledge embedded in the stories we tell about our own sound design practice as well as in the artifacts themselves.

Our approach draws on Schön's idea of *reflection-in-action*. By studying professionals in fields such as urban planning, Schön observed that, "our knowing is ordinarily tacit, implicit in our patterns of action and in our feel for the stuff with which we are dealing...our knowing is in our action" [73]. This embedded knowledge emerges through the values conflicts practitioners experience in their work. And yet, this knowledge is often inaccessible—the more skilled practitioners become, the less they think about what they are doing. Practitioners might tap into this tacit knowledge through surprise, by making familiar actions strange so that they might reflect on their particulars: "When someone reflects-in-action, he becomes a researcher in the practice context" [73]. We use retrospection to make our design practice—and the artifacts it generated—surprising and strange so that we can re-examine it with new eyes and ears in order to reflect on the knowledge embedded our past actions. By engaging reflection-*in/after*-action, we also raise questions about when, if ever, a design process is "complete."

A popular example of design retrospection is the podcast and Netflix series *Song Exploder*. Combining explanation with retrospection, musicians share digital traces of their artistic processes, such as the voice memo Lin-Manuel Miranda recorded and sent to his writing partner when he first got the idea for *Hamilton's* "Wait For It" [3]. Although not purely first-person retrospection because producer Hrishikesh Hirway interviews the musicians, *Song Exploder* inspires our work by demonstrating retrospection in service of building new capacities for listening: As the musicians tell their stories of making, they also deconstruct their songs into audio components that provide listeners with new lenses for experiencing the songs.

In our work, we seek to understand how narrative storytelling can support learning to listen to data by scaffolding sensemaking. We use first-person retrospection to access (a) the stories

embedded in the act of making the radio artifacts, and (b) stories embedded in the radio artifacts themselves. Examining our acts of making allowed us to probe how we resolved sound-design tensions, such as how to use conceptual metaphor and how to blend sound and spoken narrative. Examining the artifacts themselves allowed us to probe the extent to which we supported explanatory and exploratory modes. By focusing on these acts of retrospection, we were also able to explore what work retrospection can do for interaction designers.

3 THE NARRATIVE SONIFICATION RADIO ARTIFACTS AND HOW THEY CAME TO BE

This article examines two sonification pieces that aired on *Marketplace*, a nationally syndicated public radio show that contextualizes business and economics for general audiences. Both pieces address the economic impacts of the COVID-19 pandemic: The first, which aired on March 31, 2020 [70], conveys the volatility of the stock market via the Dow Jones Industrial Average index; the second, which aired on June 24, 2020 [69], conveys the magnitude of the unemployment crisis via new and continued unemployment claims. They both use an interview format, where the host of the show, Kai Ryssdal, interviewed the sound/data designer, Wirfs-Brock, about the sounds and asked her to explain how to listen to them.

3.1 Creating the Radio Artifacts

The first radio piece, on stock market volatility, began with a sonification project that Wirfs-Brock created and published via a video, Twitter thread, and blog.[3] The host of *Marketplace*, Ryssdal, saw the Twitter thread and asked Fam to look into producing a radio segment that mirrored the structure of Wirfs-Brock's video, which taught audiences how to listen by deconstructing the sonification into its component parts. Fam got in touch with Wirfs-Brock, who was excited about sharing her work on *Marketplace*. Several days later, they recorded an interview (between Ryssdal and Wirfs-Brock), which Fam edited into a radio segment. The core sonification design used in the radio piece (described in Section 3.3) is identical to what Wirfs-Brock originally published on her blog, although we did update it to reflect the most current data available at the time it aired.

Several weeks later, Fam pitched *Marketplace* a story where she would commission Wirfs-Brock to create another sonification, this time of unemployment claims, which give a different perspective on the economic impacts of COVID-19. Fam then contacted Wirfs-Brock, who agreed to the collaboration. Whereas the first sonification arrived at *Marketplace* fully formed in terms of sound and data design, Wirfs-Brock and Fam collaboratively and iteratively brainstormed many design elements for the second sonification: which exact metrics to focus on within the broader topic of unemployment, which time ranges to feature, and how the data should be mapped onto the sounds. Along the way, we also engaged other *Marketplace* staff to weigh in on the sound design. After we finalized the sonification design, we repeated the interview process.

For both pieces, Wirfs-Brock created the sonifications by cleaning the data in Python, creating sonifications using TwoTone,[4] and tweaking them in Adobe Audition.[5] For the unemployment sonification, she also used drum sounds from Freesound,[6] which she manually edited in Audition. For both pieces, Fam asked for a sound library of the sonification components, which Wirfs-Brock created and shared. Using this sound library, Fam created a rough outline and question topics for Ryssdal to use during the interview. Then, Ryssdal and Wirfs-Brock recorded the interviews

[3] https://medium.com/cuinfoscience/sounds-of-a-volatile-stock-market-39ba135faa63.
[4] https://twotone.io/.
[5] https://www.adobe.com/products/audition.html.
[6] https://freesound.org/.

(remotely), with Fam listening in and interjecting to ask them to repeat or rephrase certain points. Fam then edited the interviews together with the sonification clips using Audition. Fam also wrote a "lede," for Ryssdal, as the host, to introduce the piece. When the segments were broadcast on *Marketplace*, Ryssdal voiced the ledes live on the air, adding some of his own minor revisions.

3.2 A Call to Listen

But now, reader, we have reached the point where you must set down this article—or open a new tab in your web browser—and actually listen to the radio pieces, available either in the supplementary materials for this article or at the *Marketplace* website[7] [69, 70]. Listening to both radio pieces will take you 13 minutes. As you listen, if you can, we invite you to participate in our reflective process by writing down your reactions: *What did you find intriguing? What did you find confusing? What did you learn?* You might also find it useful to draw the sonifications as you hear them.

We take the stance that we can know different things through listening than we can through seeing—or feeling or tasting or smelling. Any text-based description that we provide in this manuscript, however detailed, will not be able to fully capture the sensory richness of our audio artifacts. Text descriptions are *translations* that we use in addition to asking you to listen. Our perspective on translation as an interpretive, generative activity is inspired by sociologist Michel Callon, who described translation as simultaneously an act of creation and of destruction: "To translate is to displace" but also, "Translation is the mechanism by which the social and natural worlds progressively take form" [17]. We need not fear translation and displacement—instead, we can use the gaps between sensory translations as opportunities to look for new knowledge: By attending to the sound-text gap, what can we learn?

3.3 Stock Market Volatility Sonification

The stock market sonification presents two metrics—daily percent change to represent volatility and daily closing price to represent the general trend—for the Dow Jones Industrial Average index (stock ticker DJI, data source: Yahoo Finance) from January through the end of March, 2020. Figure 2 summarizes how the data were mapped onto sounds: Daily percent change is represented with piano arpeggios, over a six-octave range, with higher notes corresponding to higher percent changes; daily closing price is represented with upright bass notes, over a two-octave range, again with higher notes corresponding to higher closing prices. Both scales use the key of E-minor.

The radio segment presenting the stock market sonification, which includes the 5-minute 25-second interview Fam edited and Ryssdal's 1-minute live lede, is diagrammed in Figure 3.

3.4 Unemployment Claims Sonification

The unemployment sonification presents two metrics—new weekly unemployment claims and continuing weekly unemployment claims—for the U.S. for January through August 2009 (peak of unemployment claims during the Great Recession, the economic downturn that occurred after the subprime mortgage crisis) and January through June 2020, using data from the Bureau of Labor Statistics. Figure 4 shows a conceptual diagram of how the data were mapped onto sounds. Similar to how closing price was mapped onto bass notes in the first sonification, new unemployment claims were mapped onto harp notes, with higher values corresponding to higher pitches over a four-octave range in the key of D-minor. Continuing claims are represented by drum sounds: The

[7]Stock market volatility: https://www.marketplace.org/2020/03/31/the-sounds-of-a-volatile-stock-market/.
Unemployment claims: https://www.marketplace.org/2020/06/24/heres-what-the-crescendo-of-unemployment-sounds-like/.

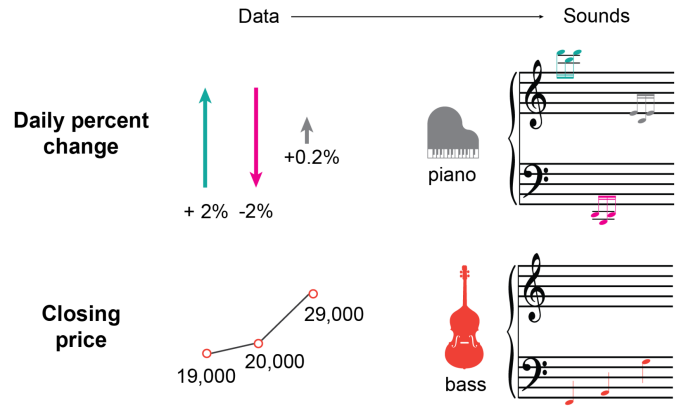

Fig. 2. A conceptual diagram of the stock market volatility sonification, showing how Wirfs-Brock mapped data Dow Jones Industrial Average data onto piano and bass notes, using pseudo-musical notation to approximate the relationship.

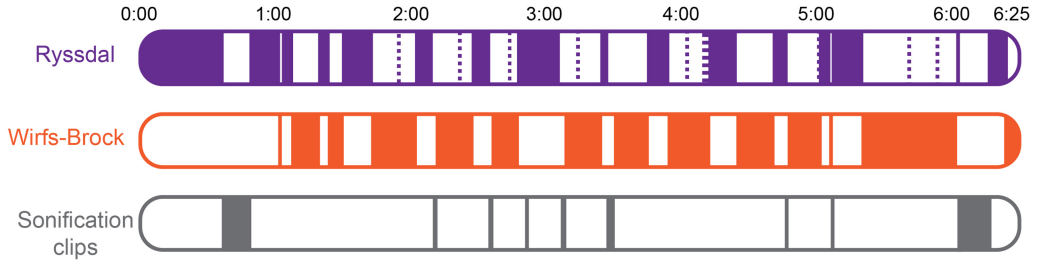

Fig. 3. A schematic diagram of the timing of the stock market volatility sonification. Main sections where the host, Ryssdal, is speaking are in purple on the top; sections where Wirfs-Brock is speaking are in orange in the middle; and sections where sonification clips play are in grey on the bottom. Moments of cross-talk, interjections, and affirmations ("mmhmmm," laughter) are indicated with dashed lines.

number of drums layered on top of each other corresponded to the number of continuing claims, in millions. As the number of continuing claims increases, the type of drum changes as well.

As with the stock market sonification, the unemployment sonification was broadcast as a radio segment, which includes the 5-minute 26-second interview Fam edited and Ryssdal's live lede (Figure 5).

4 METHODS: A FIRST-PERSON RETROSPECTIVE PROCESS

Using a research through design approach [77, 90], we examine both the artifacts we created and the processes we used to create them in order to expose the knowledge embedded in the artifacts and in our actions as designers [73]. After the radio pieces aired, Wirfs-Brock and Keegan (the fourth author on this article) wondered what the HCI community could learn from them and how they related to Wirfs-Brock's broader research on sonification and interactivity. We turned to first-person methods because, not only was Wirfs-Brock the sound designer, but her voice was also actively present in the radio pieces. To truly understand this collaborative work through first-person methods, Fam's perspective was crucial, so Wirfs-Brock reached out to Fam to participate. From there, we employed an autobiographical, research through design [90] approach—focusing on

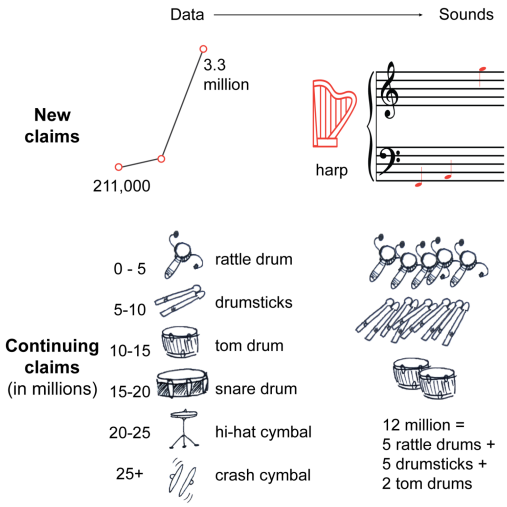

Fig. 4. A conceptual diagram of the unemployment claims sonification, showing how Wirfs-Brock mapped new weekly claims onto harp sounds and represented continuing weekly claims with layered drumset sounds. Each individual drum sound represents one million continuing unemployment claims.

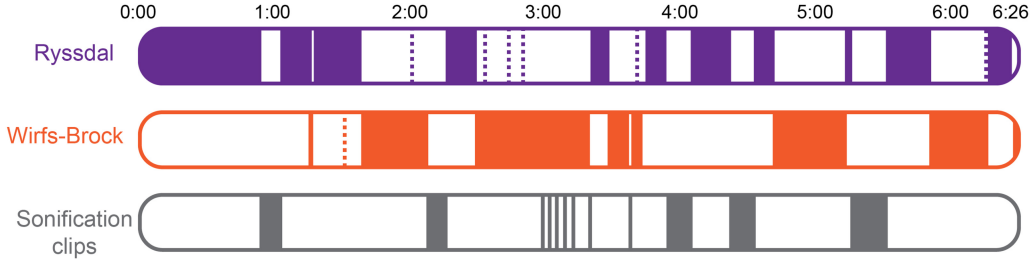

Fig. 5. A schematic diagram of the timing of the unemployment claims sonification. Main sections where the host, Ryssdal, is speaking are in purple on the top; sections where Wirfs-Brock is speaking are in orange in the middle; and sections where sonification clips play are in grey on the bottom. Moments of cross-talk, interjections, and affirmations ("mmhmmm," laughter) are indicated with dashed lines.

deliberate acts of *retrospection*—to reflect on our current sonification and narrative design practices and how those practices might shift to adapt to emerging technologies such as voice user interfaces.

We conducted a first-person, retrospective process (see Figure 6) that included: writing narratives describing our design processes, transcribing and annotating the radio pieces, drawing diagrams of the design process, and applying a *post hoc* framework of design guidelines from related fields. We chose these particular retrospective activities because they served several goals as follows:

(1) *Slowing down a rapid design process*—Journalism marches forward relentlessly. People have called it hamster wheel [79], a conveyor belt [71], "churnalism" [47]—and daily radio shows like *Marketplace* have grueling production schedules. From initial discussions between Wirfs-Brock and Fam to the broadcast dates, our narrative sonification radio pieces took 6 days and 12 days, which is short for sonification design, yet relatively long for daily news production. Furthermore, the interview portions themselves happened in near real-time (e.g., the stock market interview took 9 minutes and 15 seconds to record, which Fam edited down to

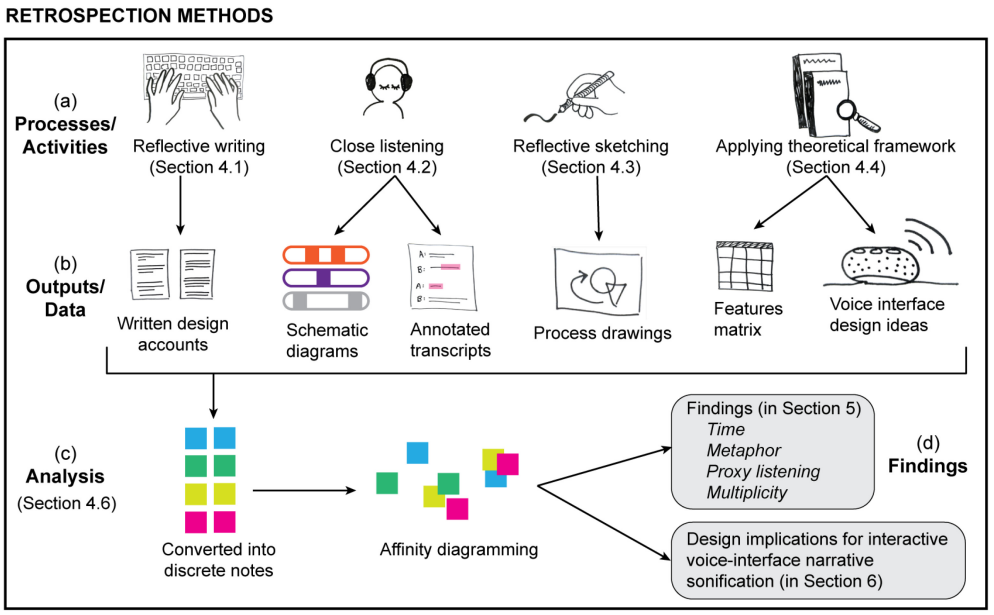

Fig. 6. This diagram outlines (a) the activities we engaged in during our retrospective process (writing, close listening, sketching, applying a theoretical lens); (b) the material data outputs they produced; (c) how we analyzed that data; and (d) where in the article we discuss the findings.

5 minutes and 26 seconds). A retrospective examination of our work allows us to decelerate this process, spending time to understand design decisions that happened in-the-moment.

(2) *Making implicit knowledge explicit*—Much of the knowledge about how to do sound and radio production well is practical and implicit [73]. Producers often go by feel or use heuristic rules of thumb to evaluate design. Through retrospection, by slowing down and explaining our decisions to each other, we made these tacit and often unnoticed practices surprising again [73], so that we could explicitly practice reflection-*in/after*-action.

(3) *Translating design practices across media technologies*—Radio has been around for more than a century and HCI would be foolish to dismiss it as an old-fashioned technology: There is a lot to learn from the accumulated knowledge of radio. How can we horizontally transfer that knowledge from people working professionally in radio to people developing interactive audio technologies, when these communities have different vocabularies, work practices, and approaches to design? One way to do this is by deliberately exposing and sharing the design knowledge of radio practitioners through retrospective reflection and analysis.

We note that a key perspective is absent here: that of the radio audience. However, in our collaborative design process, Wirfs-Brock (as sound designer) and Fam (as radio producer) served as listeners for each other, standing in for the radio audience. Thus, in our retrospective design accounts, we also reflect on how absent listeners were present in our minds.

4.1 Writing Retrospective Design Accounts

Several months after both radio pieces aired, Wirfs-Brock and Fam each wrote retrospective *design accounts*[8] describing their processes as a sound designer and radio producer. We encouraged each

[8]This is a method Wirfs-Brock has used in her personal life, as a competitive trail runner who runs races that are 100-miles or more, writing retrospective race reports to make sense of races and training.

other that these written design accounts need not be comprehensive or perfect, but could be an exercise in free-writing, and could even include stream of consciousness and emotional reactions. We did this because, although retrospection is an act of filtering a lived experience through our memories and perceptions [48], we wanted to reserve judgment on what the accounts meant while we were in the process of writing them. While writing the design accounts, we also referred to digital traces left behind by the design collaboration—e-mails we exchanged, contemporaneous notes, data files, raw sound recordings of the interviews, and so one—as memory aides. These accounts were not static documents; rather, we returned to them, iteratively, revising and rewriting as we read each other's accounts and added questions and comments. Through this process, we expanded our retrospective accounts, adding detail to them over time rather than over-writing them.

We include relevant excerpts of these written design accounts in our findings, and include the full versions in our supplementary materials.

4.2 Close Listening, Transcription, and Annotation of Radio Artifacts

Whereas writing design accounts turned a lens on our inner experiences as designers, close listening returned the focus to the radio artifacts, now with a new layer of reflection. Wirfs-Brock and Fam listened back to the radio artifacts to identify moments of interest. Wirfs-Brock also created annotated transcriptions and schematic diagrams. As Erickson wrote in his guide to video analysis, "The videotape itself is not data. It is a resource for data construction, an information source containing potential data out of which actual data must be defined and searched for" [31]. The same applies to audio recordings. Transcription is a method for analysis [58], and every format of transcription includes embedded theories that help turn sonic artifacts into an intermediate text through which we can apply an interpretive lens. In our close listening process, we were seeking data that could help us understand narrative structure and dialogic interaction as they relate to learning to listen. Thus, we annotated what each turn in dialog accomplished in terms of sensemaking. We also focused on moments of cross-talk and affirmatory utterances ("yeah," "mmmhmmm," "right," etc.), which are often excluded from transcripts yet offer details about sensemaking as an embedded social process. Full annotated transcripts are available in our supplementary materials.

To further illuminate the structures of narrative and interaction, we also created schematic maps of the radio pieces that indicate, on a timeline, who is speaking and which sonification clips are playing (see Figures 3 and 5).

4.3 Design Process Diagramming

After writing the design accounts, Wirfs-Brock sketched a diagram of her design processes (see Figure 7). This activity is inspired by the participatory practices of sketch mapping and mental mapping, which have been used in geography and education research [14, 23]. As with the written accounts, the diagram was informal, and not intended to be polished, because Wirfs-Brock wanted to access visual ways of thinking about her experience without pressuring herself to make it pretty or presentable.

4.4 Applying a Theoretical Framework

We created the sonification artifacts in a rapid fashion, guided purely by the intuitions of Wirfs-Brock and Fam as sound designer and radio producer. Unlike our other prior first-person research [34], this process did not explicitly emerge from a theoretical framework. To connect this experience of public scholarship back to the HCI research community, we chose to analyze our radio artifacts, *post hoc*, through design frameworks related to sonification and HCI. We did this by identifying design guidelines from four related areas: guidance design [18], data-driven storytelling [64], data visualization literacy/education [13], and sound studies [62].

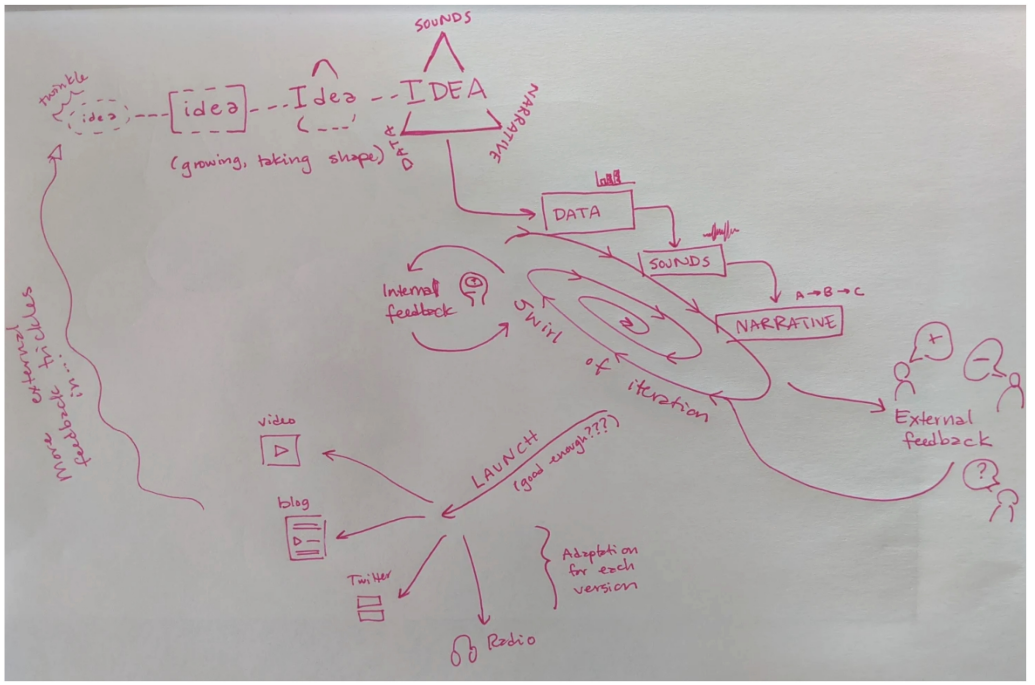

Fig. 7. Wirfs-Brock created this process drawing, which documents the steps of creating a narrative sonification from ideation to publication, including a "swirl of iteration," internal and external feedback, and how each narrative sonification leads to new ideas for future work.

We identified 29 total design principles/guidelines (between 4 and 11 from each area). For each of these design guidelines, we revisited our radio sonification artifacts and asked:

(1) *How it was applied?*
(2) *If it wasn't applied, why not?*
(3) *How might it be applied in the future if were we to adapt this content for voice or conversational user interface technologies?*

The result of this process was a design features matrix (full version in supplementary materials) that we used to dissect and analyze the radio artifacts. By challenging ourselves to consider how we might reconceptualize our radio artifacts as voice interactions, we also moved from retrospection to speculation. As a method, this allowed us to simultaneously look backward and to look forward, to speculate while grounding our speculations in the design work we had already done.

4.5 Data Analysis: Affinity Diagramming

We condensed our retrospection data—from our first-person written accounts (Section 4.1) and the digital traces we referred to while writing them, and from the design features matrix (Section 4.4)—into a set of 260 research notes, which included both direct quotes and researcher summaries. Each note, ranging from a single phrase to several sentences, captures at least one key idea, such as

> *"I balance the questions the current moment poses, and what value I hope this interview can offer our audience"* (from Fam's first-person account)
>
> *Used speech-based annotation (you are about to hear X...) that are in series (not parallel) with sounds* (from the design features matrix)

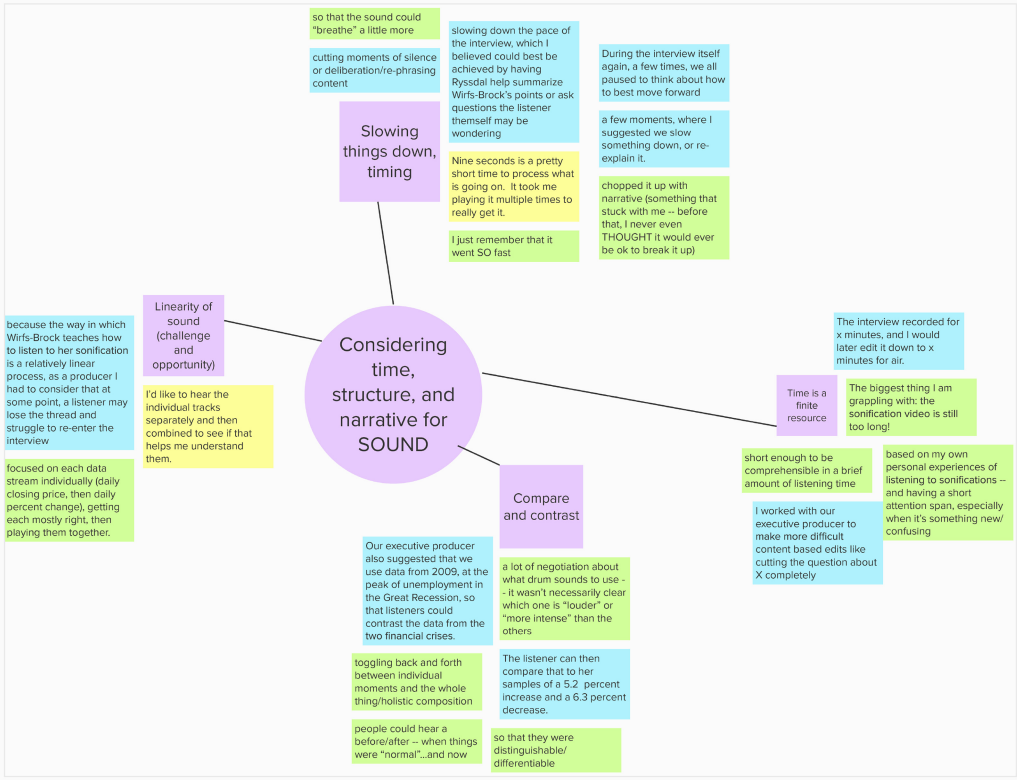

Fig. 8. This section of our affinity diagram shows varying perspectives on time and the linearity of sound. Wirfs-Brock's first-person notes are green, Fam's are blue, feedback from peers are yellow, and meta-labels describing the affinity clusters are purple.

We then analyzed these notes through affinity diagramming [42], an inductive process through which themes can emerge from the data. This process involved clustering the notes into thematic categories, labelling those categories, and clustering the categories into meta-themes. We iteratively repeated this process, using the digital tool Mural[9] (example in Figure 8), until we reached agreement on the themes.

4.6 Writing a Manuscript as Meta-Retrospection

We consider the process of writing this manuscript for an external audience to be a continuation of our first-person retrospection process. While writing, we turned our attention to what retrospection allowed us to learn. Because writing this manuscript is a crucial part of our retrospection method, we want to acknowledge the backgrounds we each have and the roles we played: Wirfs-Brock is a Ph.D. student and former data journalist with experience in radio and podcasting. She was the primary architect of the manuscript. Fam worked at *Marketplace*—her second job in radio—from January 2020 to February 2021, first as a production intern and then a production assistant.[10] In addition to writing a first-person design narrative, she also asked questions of Wirfs-Brock's

[9] https://app.mural.co/.

[10] After we submitted the first draft of this article, Fam accepted a new position as the health and equity reporter at New Hampshire Public Radio.

narrative that guided the direction of the data analysis. Devendorf is an assistant professor in the ATLAS Institute who supervises the Unstable Design Lab, where Wirfs-Brock collaborates. She helped frame the methods in terms of how they fit into broader themes within the HCI design community and shaped the structure of the manuscript. Keegan is an assistant professor in Information Science and Wirfs-Brock's advisor. He offered feedback, guidance, and brainstorming support throughout the sonification design process. He also helped frame the main arguments of the manuscript. All authors edited several manuscript drafts.

Together, the varied elements of our first-person retrospection process allowed us to document, organize, and interrogate our own thinking about the role of narrative in learning to listen to data. Through this process, we examined how we grappled with tensions around the role of sonic metaphor and the balance between explaining, as authors, and leaving room for the listener to explore. Our first-person retrospection process also allowed new themes to emerge around narrative sonification design.

5 FINDINGS

Our multiple methods of retrospection led us to understand our radio artifacts from many angles and gave us the ability to consider representative moments within the artifacts from multiple temporal perspectives (our selves frozen-in-time via the transcripts and our selves looking back from the design accounts). Through our retrospection process, we identified several themes that interaction designers, especially those working in voice and sound, can adopt as they support users in understanding data: (1) attending to *temporality and ephemerality*, (2) building shared understanding through *sonic and linguistic vocabularies and metaphor*, (3) probing the *proxy listeners* that exist in designers' minds, and (4) embracing *narrative multiplicity*.

In this section, we scaffold our findings in these four areas through a series of illustrative moments from the radio artifacts, which we present as quotes along with a call-out figure that indicates where the moment occurred within the timeline of the radio piece. We trace each of these moments as they appeared in our annotated transcripts (Section 4.2), our retrospective design accounts (Section 4.1), and our theoretical framework matrix (Section 4.4).

5.1 Tensions between Radio, Time, and Interaction

In this section, we explore how we grappled with radio's unique relationship to time throughout our design process and consider how we can apply alternate conceptions of temporality from related fields.

5.1.1 The Role of "The Clock" in Radio. In radio, time is an ever-present, one-way force pushing content forward. As noted in the *99% Invisible* podcast episode "The Broadcast Clock," clocks are everywhere in radio studios and dominate the discourse of production—the clock even makes its way into radio producers' dreams [49]. Temporality dominates the experience for listeners as well: Listeners cannot pause and they cannot skip backwards or forwards, a convention that podcasting and streaming audio has disrupted.[11]

We approached the inherent linearity of sound as both a design challenge and an opportunity. In the radio interviews, instead of taking time for granted, we explicitly discussed time and called listeners' attention to it. For example, here is how Ryssdal sets up the first sonification clip in the stock market piece (Figure 9):

[11]Note that *Marketplace* is first broadcast as a terrestrial radio programme and then later published to streaming podcasting platforms.

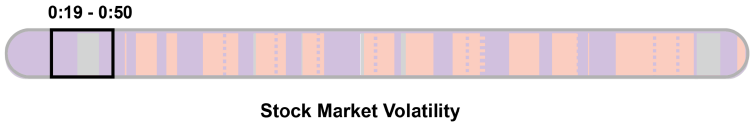

Fig. 9. Lede that introduces the stock market sonification.

*Ryssdal: And if you've spent **even a minute** looking at a stock chart, you know all the ups and the downs are a bit overwhelming. So how 'bout some sound? An audio representation of the movements of the Dow Industrial, January 2 up to last Friday, that's the 27th of March. Here you go.*

[Sound clip plays]

*Ryssdal: That was **12 or so seconds** of sound.*

At the very beginning of the piece, Ryssdal puts the listener in a temporal mindset by explicitly calling out the time a listener may have spent looking at a visualization and quantifying the amount of time the listener just spent hearing the sonification.

5.1.2 Stretching and Compressing Time to Make Room for Narrative. In our retrospective design accounts, both Wirfs-Brock and Fam treated time as a finite resource we needed to carefully manage. We were aware of the demands we would be making on listeners' time. Wirfs-Brock, reflecting on designing the stock market sonification, wrote, "The biggest thing I'm grappling with: [it's] still too long!" She wanted the sounds to be "short enough to be comprehensible in a brief amount of listening time." She even brought these concerns up during the radio interview (Figure 10):

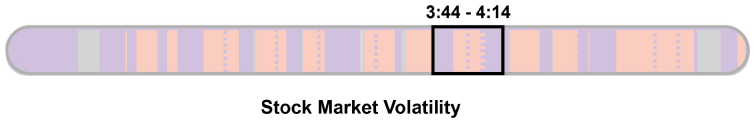

Fig. 10. Exchange about the length of sonifications.

Ryssdal: Can I ask you about timing here for a second? The 11 second clip we played in the beginning, that was like 3 months of the market, right. So what's your time frame, your reference frame?

*Wirfs-Brock: Yeah, so what I did was I sped it up so you can hear 5 days in a second. So each single day [[Ryssdal: hmmm]] is going to be 0.2 seconds. That was so you could hear the whole thing [[Ryssdal: Right]] in about 12 seconds. [[Ryssdal: chuckles]] You know, **if this thing was really long, if it was like 20 minutes, no one would want to listen to it.***

Ryssdal: [Laughs, crosstalk] Yeah, that is true. And also this entire show is only 20 minutes and 45 seconds.

Whereas Wirfs-Brock strove to *compress* time by shortening the sonifications, Fam focused on *stretching* time for the listener through the narrative of the interview. She wrote about the importance of "slowing down the pace," through Ryssdal's questioning and summarizing and through her own producer interjections, "where I suggested we slow something down, or re-explain it." During the editing process, Fam also struggled with, "how much silent space to leave in between the sounds and the voices of Ryssdal and Wirfs-Brock. This was something I worked with our

executive producer on, as she felt I wasn't leaving enough space for the listener to really sit with the sounds." Although Wirfs-Brock and Fam used different tactics, we both worked towards the same goal: manipulating time to make room for the narrative explanation and reflective silence that the listener needed in order to understand the sonifications.

While designing the sonifications, Wirfs-Brock used linearity as a tool to isolate sonic components, isolating "each data stream individually...getting each mostly right, then playing them together." We reproduced this structure—a cycle of decomposing and recomposing sounds—in the radio interview. However, as Fam wrote, this "relatively linear process," meant "at some point a listener may lose the thread and struggle to re-enter the interview." We addressed this tension of linearity and ephemerality by using the conversation between Ryssdal and Wirfs-Brock to hearken back to what the listener just heard, and to foreshadow what the listener is about to hear. This afforded, within a linear format, analytic acts of listening such as contrasting different sonified datasets.

5.1.3 Time to Sequence, Chunk, and Scaffold. Through our process of applying a *post hoc* theoretical framework, we developed new ways of thinking about time: Instead of focusing on pace and quantity, we considered how time was structured and sequenced.

Drawing from research on how people perceive sounds [11, 28, 81], we were able to consider how our audience may move through many ways of listening over the course of a single radio story. As people make sense of soundscapes, they transition from listening to describe into listening to understand; they "learn the 'story' of a space or situation before augmenting it with audio signals and interactions" and thus sound designers should attend to "semiotics and gestalt, not just functionality and acoustics" [28]. This allowed us to consider how our design decision to play the sonifications in their entirety at the beginning of the radio piece established an audio gestalt. With this perspective, we were able to reinterpret the structure of the interview in the unemployment radio artifact to understand how it supported learning to listen: First, we played the entire 2020 unemployment sonification, to produce an auditory gestalt [28] and to create a surprising sonic oddity that the listener would need to reconcile through sensemaking [59]. Then, we decomposed the sonification into its component parts and explained what each meant. Finally, we put it back together, so the listener could hear it again with new ears and also apply their new, analytic listening skills to different data—the 2009 unemployment numbers.

Data-driven storytelling literature also helped us understand the chunking of time: Tversky, referencing [57, 74], notes that, "People understand and remember a sequence of stills composed of breakpoints better than a sequence of stills that are not breakpoints" [83]. This led us to examine the natural and imposed breakpoints in our radio interviews. In the example below, Wirfs-Brock's explanation of the sonic scale of the drumsets, peppered with sonification clips, is uninterrupted by Ryssdal, who provides affirmatory utterances and cross-talk (dashed lines in Figure 11) before and after the sequence:

Fig. 11. Drumset scale sequence, sandwiched by cross-talk.

Wirfs-Brock: Right, so this is gonna be a little bit trickier, but I think we got it, so it's gonna [[Ryssdal: ok]] be represented by a drum set. So, for one million continued claims, you'd just hear a single drum. 17 million would be 17 drum sounds, [Ryssdal: ok] and they're gonna be kind of layered on top of each other, and there's one more little sonic

wrinkle in there [[Ryssdal: laughs...ok]], which is that as you hear more drums, you're gonna hear different drums, too.

Wirfs-Brock: So, when the numbers are low, between 0 and 5 million continued claims, it's going to be a rattle drum ...

[Sound clip: single rattle drum]

Wirfs-Brock: ...drumsticks for 5 to 10 million ...

[Sound clip: single drumstick]

Wirfs-Brock: ...tom drum, for 10 to 15 million...

[Sound clip: single tom drum]

Wirfs-Brock: ...onto a snare drum for 15 to 20 million...

[Sound clip: single snare drum]

Wirfs-Brock: ...a high hat [[intonation rising, to indicate penultimate item]] cymbal, above 20 million...

[Sound clip: single high hat]

Wirfs-Brock: ...and then [[intonation signaling final sound]], we've got a crash cymbal at the peak, which is nearly 25 million continued claims.

[Sound clip: single crash cymbal]

Ryssdal: Let's say, just for instance, we had 12 [[slowing down]] million claims, what would that...sound like?

Wirfs-Brock: Yeah, so you would hear 12 drum sounds, layered on top of each other, and you'd actually hear 5 rattle drums, 5 drumsticks, and then two tom drums.

[Sound clip: 12 million claims]

Wirfs-Brock: So you hear this cacophony of drums [Ryssdal: Right] building, as it gets bigger.

Ryssdal: Which is not unlike the way the unemployment claims have been sounding. So let's listen now actually to continued claims, during this pandemic-induced recession that we are in. So here we go. Let's listen to this.

[Sound clip: Unemployment claims as drum sounds, January to June 2020]

Ryssdal's cross-talk provides breakpoints that sandwich the drumset scale explanation, aiding the listener in chunking the narrative into sub-sequences. Realizing the importance of this drumset scale sub-section, Fam prompted Wirfs-Brock to repeat it when the interview was being recorded. By turning to data visualization literacy, we are also able to understand this sequence as a series of progressively more difficult interpretive tasks, a proven scaffolding technique for teaching new skills [13].

5.2 The Role of Metaphor: Establishing Shared Sonic and Linguistic Vocabularies

In the radio pieces, we used an approach of training listeners how to activate their analytic ear by introducing sounds and, then subsequently, interpreting them through narrative, simultaneously building a shared sonic and linguistic vocabulary. But this process of building a shared

vocabulary—a vocabulary that included words, sounds, and metaphor—occurred during our design process as well: The structure of the radio artifacts mirrored the process Wirfs-Brock and Fam went through as designers and producers.

In the stock market radio artifact, before even playing the initial sonification clip, Ryssdal begins to build a shared linguistic vocabulary with the listener by labelling and defining the concept the piece will be exploring, *volatility*, in the lede (Figure 12):

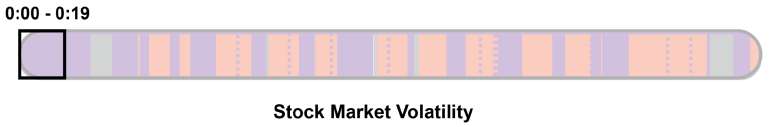

Fig. 12. Lede the includes definition of volatility.

> *Ryssdal: The defining marker of this crisis, so far we outta say, 'cause come Friday it's gonna be unemployment. But the early telltale sign that something evil was this way coming was the stock market going bananas.* ***Volatility is the technical term for that.***

This pattern of defining key words—words that would help listeners ultimately understand sounds—continued with the first question Ryssdal asked Wirfs-Brock (Figure 13):

Fig. 13. Beginning of interview defining sonification.

> *Ryssdal: So let's do a little definition here.* ***Sonification is...what...?***
>
> *Wirfs-Brock: Sonification is any technique for taking sounds and using those to convey data or information. So that could be anything from an alarm to an algorithmically composed piece of music.*

The radio pieces extended this structure, of defining and then demonstrating concepts, to learning to listen to data-derived sounds. But this process, of building shared sonic and linguistic vocabularies, started well before we recorded the interview. As Fam and Wirfs-Brock were preparing and designing, they developed their own shared vocabulary, which they "spoke" with each other by creating and exchanging intermediate artifacts.

5.2.1 Building Common Vocabularies through Sharing Intermediate Artifacts. During the sound design process, Wirfs-Brock developed her own internal vocabulary to describe and understand the data, to think about the sounds she was making, and to communicate those ideas to Fam. Wirfs-Brock began her design process by making or looking at visualizations of the data. The visualizations, "got me thinking about the shape—how fast things rose, how fast they dropped, and how pronounced any 'peak' may have been." Wirfs-Brock then used this visual vocabulary to develop a sonic vocabulary, as she "turn[ed] an analog scale into discrete buckets, so that I could match those categories with my voice (whisper, speaking, shouting, LOUD shouting)." She even "thought of the drum buckets as like a choropleth map." Fam and Wirfs-Brock grew this design vocabulary together through phone conversations about what sounds to use. Fam recalled, "visualizing [unemployment claims] with Wirfs-Brock as an empty room, and then say for every 1 million claims a person plays a kazoo." Wirfs-Brock tried this idea, but felt, upon listening, that

it was too humorous for the data it was representing. This collaborative vocabulary building was more pronounced in the second sonification, both because Fam and Wirfs-Brock had built a rapport and because we collaborated more closely on the sound design.

As we prepared for the interview, Wirfs-Brock and Fam created and exchanged various intermediate artifacts that helped cement their new shared linguistic and sonic vocabulary. Wirfs-Brock shared her draft sonifications with Fam in the form of a voice memo she recorded of herself narrating and explaining what the sounds meant—a prototype for the later interview. As Wirfs-Brock noted, the script she wrote for the voice memo was also, "a tool to figure out what supporting/scaffolding sounds I would need to make." Fam stood in for *Marketplace's* listeners, providing her own ear in lieu of the audiences.

For both radio pieces, Fam requested that Wirfs-Brock send her a folder of sound files, which she referred to in her retrospective design account as a "'sound library' of the different elements." This sound library served as a common corpus that she, Wirfs-Brock, and Ryssdal could reference. Wirfs-Brock shared the sound library with a textual key explaining what each sound file represented. Fam then created another intermediate artifact, a rough outline of the flow of the interview, which she described as recreating the narrative of "building a listeners sonic vocabulary and then 'testing' them on it," that she had observed in Wirfs-Brock's original video of the stock market sonification. In this interview outline, Fam referenced the sounds in the library as "teaching tools," and described what Ryssdal and Wirfs-Brock would be doing as "training." Thus, by giving names to the process that the listeners would be undertaking, Fam created a shared linguistic vocabulary to describe the act of learning to listen.

5.2.2 How Narrative Flow Emerged from a Shared Vocabulary. When we recorded the interviews, Ryssdal, Wirfs-Brock, and Fam could not hear the sound clips, which Fam added in during post-production editing. But, because we had already established a shared sonic vocabulary through an iterative process of making and co-interpreting, as well as a linguistic vocabulary to describe and refer to those sounds, we were able to hold them in our heads as we discussed them. However, the first interview got off to a rocky start. After listening back to the raw audio of the interview, Fam wrote in her retrospective account:

> *Ryssdal began to dig into the volatility metric, saying that what we'd heard (referring to the full sonification) "objectively was a lot to take in, so let's break it down for people, volatility is represented by, and we've got the sound library here." And then he began to trail off for a moment saying "this is um...this is volatility, hmmm how are we gonna do this Alli?"*

Fam recalls (her voice was not recorded) that she suggested slowing down the interview by playing the various different volatility sounds from the library, then building back up to the entire sonification. After that, Fam wrote:

> *[Ryssdal] apologized briefly to Wirfs-Brock for the pause in the interview, saying "Jordan, we're working this out in real time as you can tell." Wirfs-Brock replied "Well, haha that's the challenge with this stuff, people don't know how to listen." And Ryssdal used her offhanded remark as a way to move forward... He restarted the interview with the question "Part of what we have to do here in this interview right, is train people how to listen to this thing?" And then, having established to the listener the plan "training" people to listen, he smoothly transitioned to the next part of the interview...*

The narrative structure of the radio interview emerged through this interaction between Fam, Ryssdal, and Wirfs-Brock, with Fam facilitating by acting as a proxy for the radio audience. This

process was mediated by the shared linguistic and sonic vocabularies we build through intermediate artifacts. We then applied this model, developed on the fly while doing the first interview, to the second interview as well.

5.2.3 The Role of Metaphor in Sensemaking. By applying a *post hoc* theoretical lens, we were able to better understand how our emergent sonic and linguistic vocabulary contributed to acts of perception and sensemaking. Drawing from sound studies and education, we can understand how perception—including the perception of sound [12, 28]—and sensemaking function by connecting new information with past memories, experiences, and previous interpretations of the world [59]. Metaphor can assist with this process by linking new experiences to existing knowledge. Analyzing the radio pieces retrospectively, we focused on how the narrative structure of the interview supported sensemaking among listeners by stepping them through a process akin to "iteratively proposing and connecting up different ideas on the subject" [59]. For example, Wirfs-Brock uses visual, linguistic metaphor to introduce the 2009 unemployment sonification; she also frames it in terms of the 2020 sonification, which the audience has just learned how to interpret (Figure 14):

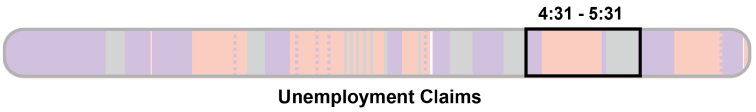

Fig. 14. Describing 2009 unemployment claims data in terms of visual metaphor, comparing to 2020.

> *Ryssdal: Ok, so, do me a favor would ya, and I'm gonna guess you have this in your data set somewhere, what does 2009 sound like, just as a point of comparison?*
>
> *Wirfs-Brock: Yeah, so 2009, we're actually gonna hear from January through August, and* ***it's gonna sound really flat*** *[[questioning intonation]], and like it's not changing that much compared to 2020. So, I don't know, another way to put that is, what you just heard, 2020, it's like this steep, sudden rise, whereas 2009, it's so long, and so gradual, and so, um, drawn out, that it's* ***hard to even hear a peak*** *when you listen to it.*
>
> *Ryssdal: All right, so we'll listen to that, here we go.*
>
> *[Sound clip: Sonification of new and continuing unemployment claims, Jan. to Aug. 2009]*

In this clip, Wirfs-Brock struggles a bit, as indicated by her pauses and questioning intonation, to put the trends into words, interpreting and processing the gist of the data. She uses visual metaphors ("flat" and "steep") to convey the "shape" of the sound that the listener is about to hear as compared to the sound that the listener just heard.

5.3 Engaging the Listener as Self through Proxy Listenership

In terms of narrative sonification, metaphor can be employed both in the speech that scaffolds the sounds, as well as the sounds themselves. While we were preparing the unemployment claims sonification, we grappled with exactly how to connect the sounds to a potential listener's past lived experience. As Wirfs-Brock created various sonification designs and shared them with Keegan and Fam, who shared them with Ryssdal and *Marketplace's* executive producer, tensions emerged between how they perceived these sonic concepts, as direct first-person listeners, and how they perceived them through the proxy audiences they had created in their own minds.

5.3.1 Editorial Judgement as Standing in for the Audience. In an early draft of the unemployment claims sonification, Wirfs-Brock had created a reversed-scale using a harp for new claims—where

lower pitch corresponded to more claims and vice versa—because she "felt like high notes tend to sound GOOD," thus emphasizing that fewer claims, with a higher pitch, would sound like the economy was doing well, which was not the case. Wirfs-Brock shared this version with Keegan. He felt this reversed scale accurately represented the nature of the data. However, when Fam played this version for her *Marketplace* colleagues, they said this reversed scale would not track with their audience because it would clash, metaphorically, with the mapping of lower numbers onto lower-pitched sounds, creating a cognitive dissonance in the listeners' minds. Rather than reacting solely as a first-person listener, as Keegan had, the radio producers were able to also listen on behalf of their audience.

Furthermore, we also grappled with whether to use the sonic metaphor of a human voice to convey the continuing unemployment claims. In the first draft, Wirfs-Brock used her own voice instead of a drumset to convey a cacophony of continuing unemployment claims. While Fam liked the emotion this version evoked, and found it disorienting in a way that mirrored the disorienting nature of the data, her editors at *Marketplace* thought it was too "editorial" because it told listeners how they should feel about the data.

5.3.2 Conjuring a Proxy Listener. Listeners may disagree on which data representations are easiest to understand. These examples demonstrate how Fam and Wirfs-Brock negotiated between being first-person listeners, listening to sonifications for themselves, and being proxy listeners, listening through the ears of an imagined audience. They negotiated these tensions by bringing in the ears of their colleagues, who *also* listened as themselves and as an external audience. Throughout the design process, Fam and Wirfs-Brock held various mental models of the audience in their minds. Wirfs-Brock noted that she was aware of "some imaginary person," but reflected that she knew little about this person, other than that they "had never heard of sonification before." Fam's job as a radio producer is to have a clear model of the audience in her mind, and her model reflected the diversity of *Marketplace*'s listeners: "There are millions of listeners, and each brings their own lived experience, race, class, gender, political alignment, understanding of the economy, *etc.* to how they listen." Fam fleshed out her understanding of the listener with knowledge of broader social and economic issues, such as "nearly half of Americans are not invested in the stock market at all." She was also keenly aware of who is "doing the telling" and who has a voice of authority. Fam wrote:

> *...news has historically been, and to a large extent, continues to be, filtered through the perspective of mostly straight, white, wealthy men. Meaning that most news has been what this population deems newsworthy, and is told in a way that explains the stories as they understood them. This has the effect of disempowering any perspective, or story that another person or group of people may have to offer.*

Through retrospective reflection, we saw how Fam balanced herself as listener and herself as proxy for the audience, while also being aware of her critical role in reshaping historical news disparities.

5.4 Multiplicity in Listening: "There is Never One Way to Understand the Economy, Ever"

Our first-person retrospective process allowed us to examine the narrative lenses we used as people who were "doing the telling." The radio pieces presented multiple narrative lenses, balanced by the structure of the interviews, the style of the conversation, and the characteristics of sonifications. As Fam wrote in her design account, "There is never one way to understand the economy, ever." During the design phase, both Wirfs-Brock and Fam held, in their minds, multiple versions of the listener, multiple versions of the narrative, and multiple versions of the sonifications. Viewing

our artifacts through a *post hoc* theoretical lens helped us think about narrative sonifications as adaptable, flexible artifacts, and to focus on the moments where we called the listeners' attention to this multiplicity.

This moment contains two simultaneous narratives—the narrative of teaching the audience how to listen, and the narrative of stock market volatility (Figure 15):

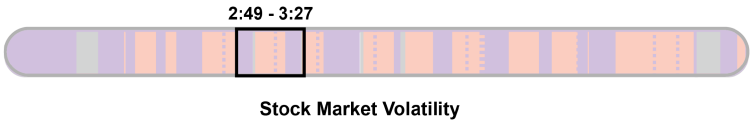

Fig. 15. Simultaneous narratives of training the audience's ear and of stock market volatility changing over time.

> *Ryssdal: All right, so let's call this a midterm exam here, if we're training people how to listen to this stuff. We're going to play, I guess it's a two-week segment of regular, plain old volatility. And then we're going to come back. So here it is.*
>
> *[Sound clip: Two weeks of steady daily percent change, isolated]*
>
> *Wirfs-Brock: So that was back at the beginning of the year, way back in January. Which... hard to even remember what that was like, right? [[Ryssdal: Yeah no kidding]] And you just hear it's kind of flat. Things aren't changing. They are kind of boring. They're kind of steady. So we're hearing a little bit of an increase, but overall they aren't really doing much.*
>
> *Ryssdal: Ok, now here's some craziness from more recently. Here you go.*
>
> *[Sound clip: Two weeks of volatile daily percent change, isolated]*

Ryssdal reinforced the narrative of training and learning through phrases like "midterm exam," and Wirfs-Brock reinforced the narrative of volatility by contrasting the current state of the world with the "boring" and "steady" state of things in the pre-pandemic data.

5.4.1 Multiple Audiences, Narratives, and Sound Concepts. Fam described her role as a producer as suggesting narratives that Ryssdal, as the radio host, can embody by having a conversation with the guest. For the stock market sonification, Fam noted that, "there were several key narratives at play; one was the story of how the stock market had been reacting to the COVID-19 outbreak. The second was the story of data presentation and how we consume it. And the third was Wirfs-Brock's personal story of creating sonification and interacting with the data." These multiple narrative lenses were present in *both* radio pieces through how the content was introduced, how it was structured to serve as a training session for listeners, and the presence of Wirfs-Brock both as a guide to Ryssdal (and by proxy, the listeners), as well as someone who, at times, despite being an "expert" guest, grappled to understand and sonify the data. This is demonstrated in how the unemployment piece concluces (Figure 16):

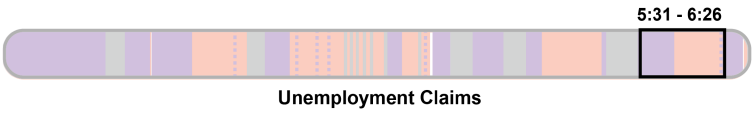

Fig. 16. Multiple narrative lenses: Creating and interpreting sonifications.

> *Ryssdal: All right, so look, last thing, and then I'll let you go. And first of all, thank you for doing this for us, because it's a really interesting way to think about, um, the data that we*

> *use on this program day in and day out. But I want to ask you, as an information sciences person, what did you learn? What was the challenge? How did you approach this?*
>
> *Wirfs-Brock: Yeah, so it was actually a really tough data set to turn into sounds. Um, and it's because 2020 is so astonishing, right, those unemployment numbers for 2020 were so huge, that to make sounds that could capture both the current moment and something like the Great Recession in 2009, um, it was quite a challenge. And I think that made me reflect on just how kind of unprecedented this current moment really is.*

This reflection on how difficult the unemployment claims data were to sonify—which Fam, as a producer, consciously did *not* edit out, even though the piece was already quite long—ties together the multiple narratives that Fam identified. In these radio pieces, the sonifications were not presented as easy or straightforward to interpret or to create. This is a difficult line to walk, and public-facing data-driven narratives are often not presented this way. But this commitment reflects Wirfs-Brock's stance during the design process that the data do not necessarily have an obvious or "right" representation. In the blog[12] Wirfs-Brock published about the stock market sonifications, she actively invited suggestions for improving and modifying the sonifications. Furthermore, when Wirfs-Brock provided a second draft of the unemployment sonifications to Fam, she also created a "just for fun version that was double speed" to provide a comparison point and emphasize that these particular sonifications are one of many ways to understand the data.

Whereas Wirfs-Brock was aware of multiple sonic interpretations, Fam was aware of multiple long- and short-term social and economic narratives. Fam wrote, "it is in all of our listeners' best interest to consistently offer a narrative lens through which our audience can understand the economy that pushes back against the historical narrative lens." One of the reasons Fam reached out to Wirfs-Brock to do a second sonification on unemployment was that, in the intervening months as the pandemic grew more severe, it became increasingly clear that the true economic impacts could not be captured by the Dow Jones Industrial Average. "The stock market is not the economy" became somewhat of a mantra on *Marketplace*. Thus both radio pieces, together, were part of an emergent, over-arching narrative to which Fam and Wirfs-Brock attended. Wirfs-Brock wrote, "we were right in the midst of the crisis, thus what even was a peak? Were we at the top? In the middle? I had to design them nonetheless, treating the current moment as a peak." Fam also had to balance the long-term knowledge of regular *Marketplace* listeners, who hear narratives unfold the show over time, and drop-in or first-time listeners.

5.4.2 Treating a Narrative Sonification as an Adaptable Object by Emphasizing the Seams. By imposing a *post hoc* theoretical frame, we considered how the narrative sonification radio artifacts themselves, as well as acts of listening, unfold as a series of multi-layered experiences: there are *layers of sound*; *layers of knowledge*; *layers of listening modes*; and *layers of creator and listener intention*. We take interest in moments when the narrative called attention to these multiple layers of experience, such as (Figure 17)

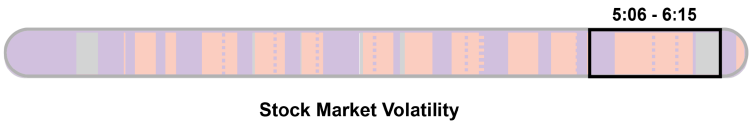

Fig. 17. Ryssdal asks Wirfs-Brock to reflect on what we can learn from sonification.

[12] https://medium.com/cuinfoscience/sounds-of-a-volatile-stock-market-39ba135faa63.

Ryssdal: Ok, so as you sit there as a PhD student in...in information science, what do you want people to get out of this?

Wirfs-Brock: Yeah, so I think that listening to data, as opposed to looking at it, can really invite people to reflect and engage in a different way. And you kind of pause and you're like oh, what's that. And you kind of pay attention to new dimensions. So the dimensions that I wanted to bring out here was that volatility, um, [[laughs]] which is actually something I learned from listening to Marketplace [[Ryssdal: laughs]], is that it's not just what direction things are going in, but how much they're swinging day to day. And so at the beginning of the sonification, things are kind of moving along, chugging along, everything sounds kind of boring, and then toward the end of it things get crazy, right? [[Ryssdal: Mmmhmmm]] They are up and down and up and down [[intonation fluctuates, emphasizing this movement]], and so you can just hear that difference in the whole texture of what the Dow is doing.

Ryssdal: All right, here it is, we're going to play it one more time, the whole 12 seconds.

[Sound clip: entire sonification, all parts together]

This excerpt explicitly highlights different types of sounds (when Wirfs-Brock described the patterns in the sonification with words, she also used the intonation of her voice to echo the pitch changes in the sonification), how knowledge accumulates over time to inform our interpretations of data (how learning about volatility on *Marketplace* unlocked a new interpretation for Wirfs-Brock), modes of listening (i.e., pausing, listening for a texture), and Wirfs-Brock's dual roles as creator and listener/interpreter of sounds.

We turned to the field of guidance design, which considers mixed-initiative interfaces for data visualization and analytics, to consider new ways of thinking about interaction in the (mostly) one-way medium of radio. According to Ceneda et al. [19], effective guidance needs to be available, trustworthy, adaptive, controllable, and non-disruptive. In *Marketplace*, trust is in part established by the presence of a consistent, well-respected host, Ryssdal, who commutes that trust onto the guests he interviews. The show is also adaptive, although not in real-time—between the first and second radio pieces, Fam ensured that the content of the second sonification adapted to the emerging narrative of the pandemic, in order to best meet the listeners' needs. The listener holds the ultimate control over the guidance *Marketplace* provides—the ability to turn off the radio at any time. Ceneda et al. also note that guidance can and should vary in heavy-handedness: It can orient, direct, or prescribe how a user should be interacting with the data. Throughout the radio pieces, Ryssdal and Wirfs-Brock moved back and forth between these levels of guidance.

We also considered Supper and Bijsterveld's work on listening modes in the sciences [11, 81], which puts acts of listening on a two-dimensional axis: listening purposes (to monitor, to diagnose, and to explore) and listening modes (synthetic, analytic, and interactive). The radio artifacts guided the listener between synthetic and analytic modes, the former when the listener is listening for narrative and explanation, and the latter when the listener is listening closely to the sonifications. Applying this frame exposed how the narrative of the interview cued the listener to get ready for these shifts in listening. In the unemployment sonification, when Ryssdal says: "We've got the harp sound for the new claims, the layered drumset thing for the continuing claims. If we put it all together, and people, everybody listening, you need to concentrate on this, here's what 2020 has been like," he is signaling to listeners, through a narrative seam, that they need to turn on their analytic ears.

Radio—often conceived of as a one-way, non-interactive medium—is a multi-layered, dynamic, and interactive experience. However, those multiple layers of experience and interaction do not occur through our typical interaction model of human inputs and system outputs. Instead, they occur through the multi-layered intentions of the designers and producers, which are embedded in an interview, and enacted through complex, varying acts of listening on the part of the audience, who constantly reconstitute the artifact as they perceive it. Thinking about audio technologies and listening as multi-layered experiences allows us to ask new design questions, such as: Should these multiple layers be simultaneously overlapping or intermittently alternating? How do listeners traverse these multiple layers? And how can our sonic and narrative designs support movement between these multiple layers?

6 FUTURE DIRECTIONS: FROM LISTENING TO DATA TO TALKING WITH DATA

As we considered what principles of guidance design, data visualization, data-driven storytelling, and sound studies our radio sonification artifacts espoused, we also speculated how we might apply those principles to interactive narrative sonifications using voice interfaces. The full table we produced through Section 4.4 is included in our supplementary materials. In this section, we highlight select design principles from each domain, examine how these principles were present or absent in the radio pieces, and discuss how we might reapply them to an interactive narrative sonification using voice user interfaces like Amazon's Alexa, Apple's Siri, Google Home, and Microsoft's Cortana.

6.1 Guidance Design: Building an Evolving Model of Listener Needs

Guidance design, used in visual analytics, is "a computer-assisted process that aims to actively resolve a knowledge gap encountered by users during an interactive...session" [18]. It has its roots in mixed-initiative systems, where sometimes humans drive the action and sometimes machines do. Even though radio is not a mixed-initative system, we note that mixed initiatives were present in our radio pieces: Sometimes Ryssdal teed up a sonification and other times Wirfs-Brock did, thus the radio pieces are both novice- and expert-driven. Success in guidance design depends on being able to correctly identify and then address users' *knowledge gaps* [18]. For the radio pieces, Fam was responsible for taking into account the assumed listeners' levels of knowledge, and considering a wide range of knowledge gaps. While recording the interview, Ryssdal relied on Fam's understanding of these knowledge gaps by checking, "Did we get everything we needed?" In a voice user interface, however, we might be able to ask the user comprehension questions to proactively asses their knowledge gaps, and then provide content to fill those gaps.

6.2 Data-Driven Storytelling: From Explaining to Exploring

Used in journalism, data-driven storytelling includes narratives based on data, enhanced by "capabilities to walk through visual insights, to clarify and inform, and to provide context to visually salient differences" [64]. Data-driven storytelling can be simultaneously *explanatory* and *exploratory* by balancing interpretation that prescribes how the viewer should understand the data with flexible, open-ended opportunities for the viewer to analyze the data on their own [82]. Our radio pieces were mostly explanatory, as demonstrated by how we provided context and interpretations of the data. Voice user interfaces could, in addition to explaining, also nudge listeners towards exploration by asking if they would like to hear the same data, but with a different sonic representation; or to hear the same sonic representation, but for a different time period. Listeners might also be able to zoom in to examine a particular day or week in more detail.

6.3 Data Visualization Literacy: Unifying Theoretical and Procedural Knowledge

Data visualization literacy considers the skills involved in being able to "make meaning from and interpret patterns, trends, and correlations in visual representations of data" [13]. Literacy requires both *theoretical* knowledge (how a chart functions) and *procedural* knowledge (how to make a chart), which are, respectively, tied to being able to *interpret/read* and to *create/write* visualizations [13]. The radio pieces focused on theoretical knowledge when Wirfs-Brock described sounds of data trends, and on procedural knowledge when Ryssdal encouraged the audiences to practice close listening. However, on the radio, listeners are not invited to test their new knowledge by creating sounds. A voice user interface could encourage procedural knowledge by prompting users to guess the meaning of sounds before explaining what they mean ("Do you think unemployment claims were going up, down, or staying the same in the clip you just heard?"). A voice interface could even prompt users to perform/create their own sonifications ("What do you think unemployment claims sounded like when the dot-com bubble burst in 2002?").

6.4 Sound Studies: Turning on Ears by Turning on Voices

Sound studies is an interdisciplinary field that considers "the material production and composition of music, sound, noise, and silence and how these have changed throughout history and within different societies" [62]. Analytic listening is a skill that can be developed over time [11], and can be sharpened by creating with sound [7]. The narrative in our radio artifacts framed listening as a training process, progressing from simple to more complex sonifications. Extending this principle, voice user interfaces could explicitly invite the user to listen for certain sonic or data characteristics ("This time, focus on the different types of drums, to learn how to identify timbre," or "This time, try to identify the exact moment the unemployment claims peaked"). By asking the listener to share their insights, a voice interface might encourage reflection on how to listen to something is always also to speak for it [67].

6.5 Future Work: Identifying Design Patterns and Prototyping with Them

Our first-person retrospection lays the groundwork for future research that applies storytelling techniques to help people learn how to listen to data sonifications through interaction. Expanding outward from the radio pieces, we plan to use similar close listening methods with other artifacts (sonifications for radio, podcasts, museum exhibits, web publications, etc.) to identify narrative design patterns that can form a language of explanatory and exploratory narrative sonification. Then, we hope to embody the theories embedded in those patterns through prototyping and participatory design workshops. Ultimately, we hope to move towards a future where narrative and sounds are treated holistically, and sonification designers consider how people learn to listen.

7 DISCUSSION: WHAT HCI CAN LEARN FROM RADIO AND RETROSPECTION

What can research through design with radio—an "old-fashioned" technology—highlight for HCI researchers and practitioners? Radio is often live, or quasi-live in the case of *Marketplace*, and unlike many acts of design, occurs at or near the pace of human interaction. We often conceive of radio as a non-interactive medium because producers do not have access to real-time feedback from listeners. Yet producers and listeners do interact through radio: they just interact at a distance, separated by time and space. Over radio broadcasting's century-long history, radio producers have developed deep, implicit knowledge of how to interact with listeners at a distance [84]. When we consider voice and conversational user interfaces, we treat them as somehow more interactive than radio because they afford turn-taking. Perhaps this is a myth. Voice user interface designers are still separated by space and time from the people using these technologies.

Table 1. Summary of Key Insights Uncovered through the Stages of Our Retrospective Process

Theme	Insights from design accounts	Insights from *post hoc* lenses
Time	Time as something to be compressed versus time as something to stretch	Organizing time by deliberate sequencing and chunking
Metaphor	Building shared linguistic and sonic language through intermediate artifacts	Adjusting the level of metaphoric salience to match the needs of the audience
Proxy listening	Listening as the self versus listening as the "imagined" audience	Building trust through a radio host and adapting to emerging, ongoing narratives
Multiplicity	Balancing multiple data interpretations with multiple long- and short-term narratives	Calling attention to sound and narrative as dynamic objects by emphasizing the seams

Drawing from radio allowed us to first look inward and backward, so that we could ultimately look outward and forward to transfer that knowledge to designing new technologies. Radio producers have valuable knowledge that can help voice and conversational user interface designers. Our retrospective process led us to consider time, metaphor, listenership, and multiplicity in narrative sonification design. To demonstrate how the components of our retrospective process informed each other, we have summarized our findings in Table 1. In our discussion, we first explore how radio producers, who conjure listeners in their minds, provide new models for understanding users. We then discuss how radio narratives can be considered boundary objects. Finally, we turn to how retrospection, as a method and a design strategy, can support sensemaking.

7.1 Interaction at a Distance: From Proxy Listener to Proxy User

As we created our sonification radio artifacts, Fam, as a producer, was adept at holding the listener—or rather, multiple kinds of listeners—alive in her mind. The listeners may not have been physically present during our collaborative design process or during our retrospection, but they were able to carry on a conversation with Wirfs-Brock through Fam. Fam also translated that model of the listener into preparatory materials for Ryssdal in the form of an outline. Then, Ryssdal as host was able to act as a stand-in for the listener, embodying their concerns by voicing their likely questions. Our first-person retrospective process allowed us to explicitly access this model and to hear from these proxy listeners.

Turning to voice and conversation user interface design, designers still operate with proxy (often persona-fied) users, and must build presumed interactions. Our first-person reflection on radio can suggests a model of user-centered design to HCI that considers the users' needs through the first-person experiences of the designer, just as the radio listener lived in Fam's mind and traveled with her through the stages of our design process. This model raises important questions about HCI and interaction design to be explored in future research: When can the listener—or the user—live in the mind of the designer, and when do designers need to default away from their own experiences? Where do the boundaries between listeners and designers lie?

7.2 Radio Narratives as Boundary Objects

In our radio artifacts, the narrative—as enacted in Ryssdal and Wirfs-Brock's interview—served as a *boundary object* through which the producer, Fam, could interact with the listeners, and through which the listeners could interact with the sonifications. Boundary objects, as defined

by Star and Griesemer, are artifacts for communication and cooperation that "inhabit several intersecting social worlds," and are "plastic enough to adapt to local needs and the constraints of the several parties employing them, yet robust enough to maintain a common identity" [78]. The dialogic narratives enacted by Ryssdal and Wirfs-Brock served as boundary objects between the sonifications and the audience—who are diverse but also share a common identity as *Marketplace* listeners. The interview narrative contained embedded theories about the meaning of sounds, communicated via instructions for listening that the audience could adopt and adapt. Ryssdal, as the host, served as a kind of boundary character, mediating between the sounds, the designer, Wirfs-Brock, and the listener.

Thinking about audio narratives as boundary objects transforms the limitations of sound into affordances that can be traversed via narrative as a boundary-crossing device. Boundary objects, as Bowker and Star write, are a "way that the tension between divergent viewpoints may be managed" through "accommodations, work-arounds, and in some sense, a higher level of artful integration...managed by people's artful juggling, gestalt switching, and on the spot translating" [16]. The divergent viewpoints we managed—through a narrative boundary object that juggled, switched, and translated—were those of expert and novice, of creator and interpreter, of past and future. Working within the linear, ephemeral-temporal nature of sound, narrative is a boundary object that can serve as a bridge between the past, present, and future. Narrative can give instructions for future listening ("pay attention to what is about to come next") or hearken back to what was heard but is now gone ("remember when..."). By labelling sounds with words and phrases that can become a cognitive shorthand to recall them, narrative is a boundary object that crosses the boundaries of time in sound. Through treating narratives as boundary objects in the medium of sound, the apparent limitations of sound become generative rather than restrictive.[13]

7.3 Retrospection and Sparseness as Tools to Support Sensemaking

This manuscript—which we consider a continuation of our retrospective process—emerged from Wirfs-Brock's drive (encouraged by Keegan and Devendorf) to turn a collaboration with Fam and *Marketplace* from a serendipitous moment of public scholarship into a piece of capital-"R" research. In a way, we chose retrospection as a method out of necessity: In the wake of a rapid, *ad hoc* collaboration, it was the only method available to us. These types of collaborations may be messy, but they are essential for HCI researchers who hope to study real-world situations. To successfully probe the wild outside the lab [20], HCI researchers need skills for retrospection. Thus, throughout the writing process, we returned, repeatedly, to the question of what retrospection allowed us to learn.

To hone in on this theme—what work does retrospection do—we asked ourselves: *How might we have documented this project differently were we to do it over again?* Initially, we considered ways we might have captured real-time design deliberations: Perhaps we could have recorded audio of Wirfs-Brock and Fam's phone calls as we discussed the sonifications and the structure of the interviews, or video of ourselves and our screens while we edited sonifications and interview tape. We might have collaboratively annotated our design decisions using digital note-taking tools [63].

[13]Similarly, we can think of our acts of first-person retrospection—including this manuscript itself—as boundary objects. As we wrote this manuscript, we experienced several points of friction. As a mixed team of academic and industry collaborators, we had divergent goals and norms. While centering own experiences, we struggled with whether to refer to ourselves in the first-person or the third-person. We realized that we had changed since we began this project, and we were referring back to earlier versions of ourselves that were frozen in time through radio artifacts and digital traces. We faced the limitations of text in capturing the sensory experience of sound, and relied heavily on visual figures to describe our sonic artifacts. However, because we were embedded in a first-person research process, we treated these points of friction as opportunities to more deeply understand ourselves and our relationship to our narrative sonification artifacts. For example, our reliance on visuals reminded us of Mitchell's claim there are no purely auditory or visual media [53].

Or, Wirfs-Brock could even have live-streamed her design practices via Twitch, inviting listeners to glimpse—and maybe even contribute to—the evolution of the sonifications. As we re-imagined the research process, we realized that all of these efforts filled in some of the holes of our comparatively sparse retrospection process. But these efforts would have slowed down or even endangered our collaboration.

Why do we feel this epistemic pull to document and log everything, to produce "thicker" traces of our design processes? And how might that have led us to different conclusions? Reflecting on these questions, we realized that the power of retrospection actually lies in its sparseness: Because retrospection relies on partial traces, filtered through our memories about past events, it forces us to tell stories about our experiences. And through those stories, as Orr noted [61], we make sense of the world. Similar to how Dykes et al. propose that documenting design processes through comics can provide new insights by allowing the readers of comics to fill in the gaps between panels [30], sparse retrospection creates productive gaps that generate space for sensemaking. Our act of opportunistic research forced us to be sparse, which, in turn, forced us to focus on retrospective interpretation, which allowed us to focus on the *narratives* driving the process of learning to listen to sonifications.

By focusing on our own acts of making and interpreting sounds through first-person retrospection, we realized that listening to sound is, itself, a retrospective act. Sounds are inherently ephemeral. We can only actively hear a moment in time. Thus to perceive a whole sound, such as a sonification or a song, we must remember—we must retrospectively tell ourselves a story about what we just heard. For example, after repeatedly re-listening to the radio artifacts while writing this manuscript, Wirfs-Brock found herself getting riffs from the sonifications stuck in her head, much in the same way that hooks from songs can become "earworms" [46]. Sound's ephemerality enables this effect: We imagine sounds inside our minds when the sounds are no longer present. Contrast this with the phenomenological experience of looking at a data visualization: Although we blink while looking, our brains stitch this experience together into a relatively continuous, uninterrupted sensory stream. How might we see a visualization differently if we experienced it as we do sound: We might look, and then we might close our eyes, forcing ourselves to remember what we just saw, to turn it into a retrospective visual story in our minds.

Instead of treating sonification's ephemerality and perceived sparseness—guiding and orienting elements such as axes labels or titles are often not present in sonifications themselves—as problems to be solved, our process of retrospection illuminates how they are features that can support sensemaking and interpretation. The sparse design retrospection we carried out in this project centered this aspect of learning to listen by calling attention to the stories we told each other, as sound designers and radio producers, about our personal acts of interpreting and making sounds. This encouraged us to consider more deeply how we might use retrospection to encourage acts of sensemaking and interaction among listeners, audiences, and users. Our interactions with data representations—visual, auditory, or multi-sensory—do not end with our consumption of them. Rather, interactions with data continue through our interpretations and recollections of them, as we retrospectively make sense of the data we encountered, fitting it into the context of our world.

8 CONCLUSION

We conducted a first-person retrospection of two sonifications we developed for the radio show *Marketplace* and the narratives in which they were embedded. A key design requirement was that the radio segments must teach novice audiences how to listen to the data—which we implemented through narrative scaffolding. Our first-person approach allowed us to explore how we treated narrative as a boundary object as we designed radio artifacts to support people as they learned to listen to data. Through this retrospection, we identified several themes that interaction designers,

especially those working in voice and sound, can adopt as they support users in understanding data: attending to temporality and ephemerality, building shared understanding through sonic and linguistic vocabularies and metaphor, probing the proxy listeners that exist in designers' minds, and embracing multiplicity. Returning to the goals of explanatory journalism, which seeks to help people understand the complex world around them, we found that as we develop techniques for explanation and exploration, retrospection can be a powerful tool for designers to interrogate the narratives that drive sensemaking. Turning towards future work, perhaps we could build acts of retrospection into interactive technologies, encouraging acts of retrospective sensemaking among our users and our audiences.

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