Critiquing Physical Prototypes for a Remote Audience

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ABSTRACT

We present an observational study of physical prototype critique that highlights some of the challenges of communicating physical behaviors and materiality at a distance. Geographically distributed open hardware communities often conduct user feedback and peer critique sessions via video conference. However, people have difficulty using current video conferencing tools to demonstrate and critique physical designs. To examine the challenges of remote critique, we conducted an observational lab study in which participants critiqued pairs of physical prototypes (prosthetic hands) for a face-to-face or remote collaborator. In both conditions, participants' material experiences were an important part of their critique, however their attention was divided between interacting with the prototype and finding strategies to communicate 'invisible' features. Based on our findings, we propose design implications for remote collaboration tools that support the sharing of material experiences and prototype critique.

Author Keywords

Open hardware; design review; remote collaboration; video conferencing; material experience; prototype critique

ACM Classification Keywords

H.5.2. Information Interfaces and Presentation: User Interfaces

INTRODUCTION

Iterative prototyping is an effective way to improve design outcomes [11]; refinements to each successive prototype are informed by cycles of evaluation. Prototype evaluation can come from peers during design reviews or critiques, or from end-users participating in field testing. While visual designs can receive structured feedback from remote peers or end-users in online settings [36, 53], remote feedback on physical designs is a persistent real-world challenge. For example, online open-hardware communities collaborate remotely on computer-aided design (CAD) files for physical objects such as musical instruments (e.g., FFFiddle [1]), 3D printers (e.g., RepRap Project [2]), or prosthetic limbs (e.g., e-NABLE [3]). While shared CAD models capture the intended geometry of a design, they cannot answer questions about how a design performs in the real-world. Thus, these designs are physically produced by the community—individual designers, makers, enthusiasts, or end-users—for design feedback. The community then uses off-the-shelf video conferencing systems to virtually meet and share prototype feedback. However, standard video conferencing tools are not necessarily equipped to convey the material experiences that inform physical prototype critique. *How should remote collaboration technology support people as they critique physical artifacts?*

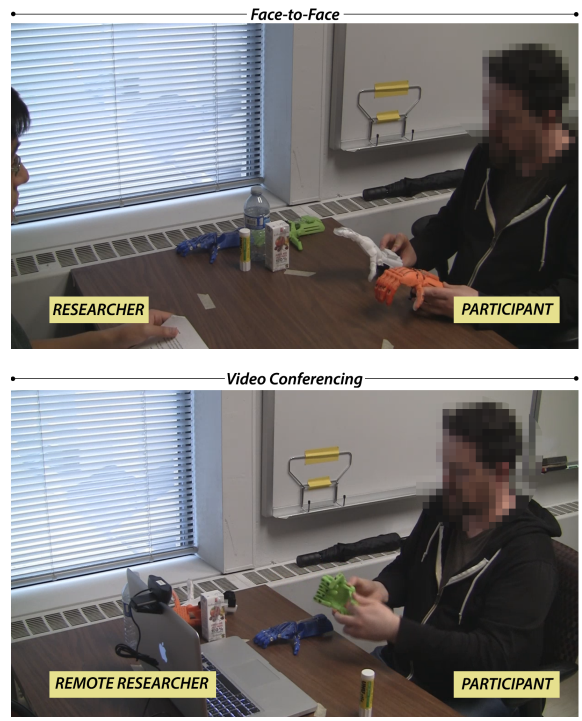

Figure 1. Participants (here, P13) critique prosthetic hands for a researcher while (Top) sitting face-to-face across from the researcher, and (Bottom) using a webcam to video conference with a remote researcher.

To establish how people communicate prototype critiques we designed and ran an observational lab study. We asked participants to compare, review, and critique pairs of complex physical prototypes—prosthetic hands from the e-NABLE community. Participants communicated their critique to a

[1]http://openfabpdx.com/fffiddle/

[2]http://reprap.org/
[3]http://enablingthefuture.org/

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collaborator in two conditions: face-to-face and video conferencing (see Figure 1). In our analysis, we examined how participants adjusted their behavior to communicate dynamic (e.g., actions, gestures) or 'invisible' (e.g., surface texture, string tension) physical qualities over video.

We found that participants in both conditions primarily focused on their physical interactions with prototypes, and only occasionally looked up to address their collaborator or preview their camera's video (video conferencing). Participants communicated fine details, prototype behaviors, and subjective experiences through verbal and visual descriptions, such as narrating their tactile experience of a rough surface or using their own body to illustrate how the prototypes performed tasks. However, when demonstrating prototypes and describing physical experiences to the video camera, participants had difficulty knowing whether relevant features of the prototype were visible to their collaborator. We contribute our observations on how people communicate materiality at a distance, and introduce a set of design implications for video-mediated critique collaboration systems that help people convey nuanced material experiences to a remote audience.

In this paper, we first review related work on materiality, remote collaboration around physical objects, and prototype critique. Next, we motivate the design of our observational lab study based on observations of video conferencing in the e-NABLE design community, and describe our study protocol. Finally, we present our findings and discuss design implications for video-mediated collaboration systems.

RELATED WORK

In the following sections we discuss related work on materiality, remote collaboration around physical objects, typical physical tasks, and design critique.

Materiality and Interaction

Materiality or the *material experience* is an emergent topic of interest in HCI research. Experiences with material forms and properties are a fundamental part of how we understand and interact with objects (e.g., [23, 32, 51]). HCI researchers have highlighted how designers might leverage physical materiality to craft an end-users experience of an interface or tool. For instance, Karana et al. [32] discussed a designer's exploration of possible material interaction for tuning a radio. In their discussion, the authors proposed a framework of four material experiential levels: *sensorial* (e.g., warm), *interpretive* (e.g., calming), *affective* (e.g., desire), and *performative* (e.g., stroking, caressing). Beyond HCI, Dant [10] identified ways in which a consumer interacts with the materiality of a product—*pausing for thought, perception and interpretation, orientation, gesturing, and manipulating.* Our work addresses how an individual's 'conversation *with* materials' is communicated to another person. Specifically, our study expands on past work by observing how material experiences inform prototype critique and are conveyed in video-mediated settings.

Remote Communication Systems for Physical Tasks

HCI researchers have long been interested in developing technology to support remote collaboration on physical tasks—specifically addressing the challenge of grounding communication based on locally-present physical objects. One approach to grounding conversation is to provide a shared view to both participants. For example, a worker can use a head-mounted camera to share their viewpoint (e.g., [16, 28]). For environments with multiple cameras, algorithms for automatic camera control (e.g., [47]) can detect which parts of a space contain action, and switch to that view. Alternatively, a shared virtual representation can act as the basis for communication [41]. While simple, this approach requires each participant to translate local experiences (e.g., troubleshooting a photocopier [41]) into a representational abstraction. Instead of sharing a view, the remote helper could also control an independent view, for example, using robotic telepresence [46] or a drone [30]. Highlighting objects within a scene can also ground conversation. For example, Fakourfar et al. evaluated different annotation techniques that are shared with a worker via head-mounted display [16]. Meanwhile, Norris et al. created CamBlend [40], which allows for pointing gestures between remote collaborators via selective focus and blurring techniques.

Tangibles (i.e. physical components) can synchronize physical attributes such as movement and rotation [4, 44], size [38], or shape [35] through physical components of corresponding objects at distributed work sites. Tangible communication interfaces such as Wrigglo [42] and Bendi [43] allow users to communicate via synchronized tangible devices. In the context of our study, the objects under discussion are actively being designed and iterated upon; the objects themselves are often one-off fabrications or contain unique end-user customizations. In these settings, the object's unique materiality and response to human action is exactly what is under discussion.

Many of the issues on remote collaboration on physical tasks identified by past work remain relevant for remote critique; we situate and contrast many of our findings in this wider body of work. However, our physical task—*prototype critique*—is fundamentally different from typical "helper-worker" collaboration on an instructional or step-by-step task.

Collaborative Physical Tasks

Most studies of remote communication with physical objects use construction or assembly tasks. In these tasks an "expert" or "helper" typically provides step-by-step instructions or a description of a known end-state to a remote "worker" who assembles, fixes, or modifies physical materials at their location. These physical tasks may include building block assembly (e.g., [2, 16, 49, 25]), construction tasks (e.g., [18, 20]), repair tasks (e.g., [21, 34]), or object placement (e.g., [50, 30]). While the helper has access to information about instructions or an end-state or goal, the worker lacks this information but instead has access to the physical media needed for the task. There are a few examples where both collaborators contribute knowledge to the problem or solution. For example, Jones et al. [30] evaluated a drone video conferencing system by having participants perform a "scan and search" task. While the remote helper was able to identify locations of markers from their aerial drone view, only the on-the-ground worker could identify the color of each object. Thus, the pair needed to combine their expertise to successfully complete the task.

In our study, participants provided feedback on hand-held physical prototypes. Unlike assembly or troubleshooting, prototype critique does not have a pre-determined process or outcome. Instead, participants were free to share their thoughts and opinions as they saw fit. Unlike a “helper-worker” task, the person giving the review has access to both key knowledge (their insights gained through material experience) and the physical artifact—the collaborator is their audience.

Prototype Critique in Collaborative Product Design

Design critique is key to the collaborative design process. Critique often occurs during a design review—a meeting where the team assesses and discusses design documents in reference to expectations, requirements, and goals [48]. Both professional software (e.g., Autodesk Design Review [3]) and research systems (e.g., DDRIVE [7]) that support design review are often centered around virtual CAD models. However, not all features of a design can be fully captured or evaluated in a virtual representation—physical prototypes are still important to check real-world performance, actual tolerances and clearances, manufacturing precision, and ease of human assembly [5, 6, 15, 37]. Bousseau et al. observed fabrication and prototyping conversations between collocated novice prototypers working in leader-assistant pairs [5]. They found that participants’ conversations alternated between a one-way presentations of design concepts and back-and-forth critiques. They suggest that remote collaboration tools support these shifting modes by including *“specialized visualization, pointing, and annotation tools.”*

Our study examines how novice end-users articulate critique of a physical prototype during face-to-face and remote communication. By observing prototype feedback conversations, we can begin to understand the emergent strategies people use to communicate their critique, material experiences, the challenges they face in using technology to deliver their feedback, and ways that new technologies might better support open-ended communication around physical prototypes.

OBSERVATIONAL LAB STUDY

The goal of our observational lab study is to understand the similarities and differences between face-to-face and video-mediated communication for the types of critique presentations that are common in open hardware communities.

Motivation: e-NABLE Video-conferences

To inform our study design, we looked to existing prototype critiques in an open hardware community—e-NABLE (prosthetic limb design and fabrication). We chose e-NABLE as it is a large active community (9215 Google+ members). We examined 10 videos (approximately two hours each) from the community’s ‘Town Hall’ and Research & Development (R&D) meetings. Furthermore, we looked at a sample of 17 videos (*duration average=4m:22s, min=20s, max=12m:58s*) posted by community members that focused on physical prototypes. In the following section we discuss how the e-NABLE video conferencing practices informed our study design.

"Show-and-Tell" Critique. The e-NABLE R&D and Town Hall meetings can have 20 or more virtual attendees. When someone presents their critique, it is a one-sided “show-and-tell” presentation, as opposed to a back-and-forth dialogue. While members of the audience occasionally ask questions, they generally do not interrupt or interact with the presenter. We chose to have each participant provide their critique to a confederate collaborator following a protocol. By controlling half of the conversation, we are able to gather consistent results from the perspective of the person presenting the critique.

Open-ended Communication. Critiques in the e-NABLE community are open-ended, without a specific physical problem that needs to be solved in that moment. In most cases, both the person giving and receiving a critique have different forms of ‘expert’ information about the prototype. The person receiving the critique is often part of the design team and understands the rationale behind the current design; the person providing the critique has real-world experience with the prototype that needs to inform the next design iteration. Our participants need to be able to freely articulate their prototype critique, and not be confined to step-by-step instructions or a specific end goal. We then can observe strategies or difficulties that only arise in relatively unstructured presentations.

Physical Comparisons. e-NABLE community members—especially prosthetic recipients—often provide prototype feedback by comparing different designs or versions during online meetings. These comparisons provide valuable information on real-world usage to designers and help the community to iterate and develop on designs. In our study, we gave participants the task of comparison to help them form their critique.

Range of Participant Expertise. Creating physical objects is no longer limited to design professionals or companies with manufacturing capabilities. For example, contributors in Town Hall meetings include hobbyist designers and makers, and prosthetic recipients. In our study, we chose to recruit novices who do not necessarily have experience with 3D printing or engineering design, to address how a non-expert end user might review a prototype.

Physical Complexity. The e-NABLE community’s nuanced remote prototype critiques are due in part to the complexity of the prototypes themselves. In our study design, our participants compare pairs of mechanically complex prototypes.

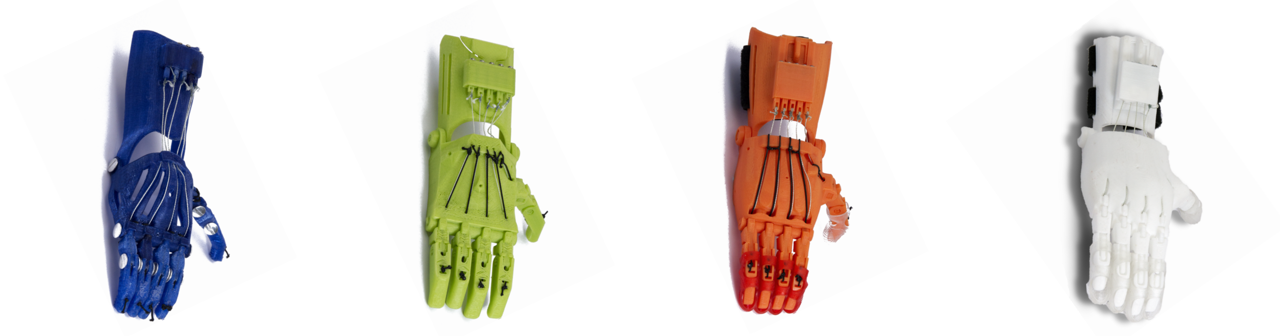
Looking for Breakdowns. At several points, presenters in e-NABLE video-conferences had difficulty using their webcam, demonstrating the prototype, or managing Google Hangouts [4]. Our analysis identified video conferencing breakdowns and unpacked how they affected the critique.

Prototypes for Review

We conducted pilot studies where participants reviewed geometrically and functionally simple objects (bottle openers). In our pilot, the participants’ brief, straightforward critiques no longer resembled the rich, complex presentations from the e-NABLE community. The simple prototypes were based on a very simple mechanism (leverage to open a bottle) and a single, simple interaction (all pilot participants mimicked the opening of a bottle prop using the prototypes).

[4] https://hangouts.google.com

Assembled e-NABLE Hands



Hand Name	Cyborg Beast	Raptor Hand	Raptor Reloaded	Phoenix Hand
Published	03/02/2014	09/29/2014	12/17/2014	03/30/2016
Print Color	Blue	Green	Orange	White
Joints	Metal screws	Plastic pins	Plastic pins	Plastic pins
String Enclosure	Exposed groove	None	Exposed Groove	Fully covered
Straps	None	None	Single, Large	Two, Small
Fingertips	Hard bumps	Smooth	Soft gel add-on	Soft gel add-on
Thumb Orientation	Perpendicular	Perpendicular	Perpendicular	Down and away

Table 1. Key design features of the 3D printed and assembled prosthetic hands used in the study.

In our study, we provided participants with pairs of already assembled e-NABLE prosthetic hands to review. The prosthetic hands are mechanically complex and require assembly of 3D printed parts with off-the-shelf parts such as screws and elastics. The hands also perform complex functions that rely on physical properties (e.g., friction, resistance, material stiffness), and require hands-on experience to evaluate their effectiveness. The four designs used in our study (see Table 1)—the Cyborg Beast [55], Raptor Hand [13], Raptor Reloaded [14], and Phoenix Hand [17]—are frequently discussed within the e-NABLE community. They represent a chronological sequence of designs, each iterating and improving upon the previous design.

We fabricated all 3D printed parts on the same 3D printer (Ditto Pro) using different colors of 1.75mm PLA plastic filament. We used the recommended 3D print settings included with the instructions for each prosthetic. We printed each hand in a different color so that participants could easily differentiate designs and refer to them by color during the study. We assembled the 3D printed parts together with necessary off-the-shelf parts (e.g., screws, barrel bolts, elastic bands, fishing line). We produced each hand at 100% scale, which is sized for a small three-year old child. All prosthetics were fully operational, but too small for any of our participants to wear.

Procedure

We began each study with an initial questionnaire on demographic information and identifying any prior experience with designing or critiquing physical objects. We then gave the participant all four hand prosthetics and invited them to physically handle and manipulate the hands. Participants were able to ask any questions about the prosthetics prior to beginning the study tasks. We also provided an empty 355mL plastic water bottle, a full 200mL rectangular juice box, and a glue stick so the participant could test grasping a range of objects.

Once they were familiar with the hands, we asked each participant to present comparisons of a specific pair of hands to a collaborator (played by a researcher). Participants were aware that the collaborator was a researcher. Each participant performed the task in a *face-to-face* (F2F) condition and a *video conferencing* (VC) condition; we counterbalanced the order of these conditions across all participants.

In each condition, the collaborator asked questions to assist the participant in providing a complete prototype review. These questions addressed (a) comparisons between prosthetics, (b) comfort, (c) functionality and usage, (d) assembly or print defects, and (e) improvements for the prosthetic hands. This structured format ensured that all participants consistently responded to similar issues across both conditions. The order of our questions was also intended to ease participants into the critique following a sequential format similar to a model for crowdsourcing critique suggested by Xu and Bailey [52]—(1) questions for the participant to simply describe the prototypes (2) asking the participant to compare and identify strengths and weaknesses of the prototypes and (3) to deliver any ideation, additional thoughts, or summary of their critique.

The collaborator's behavioral protocol allowed them to answer participants' questions on the visibility of various parts of the prosthetic (e.g., *"Can you see this?"*) or to answer questions regarding the prosthetics (e.g. *"Are these for the same age?"*), but not provide feedback on the participant's presentation. Participants were encouraged to go beyond the collaborator's questions and provide any additional thoughts or opinions they had. In the face-to-face condition we instructed the collaborator to not physically interact with the prosthetics as we did not want the collaborator's interactions with the prototypes to

	5-point Likert Agreement Medians by Condition	
Question	*Face-to-Face*	*Video Conferencing*
I had an easy time communicating to my partner	3.0	3.0
It was easy to handle the prosthetic hands	3.0	3.0
(*) I felt like my partner was able to see what I wanted them to see	3.5	2.0
(*) I knew what my partner was looking at most of the time	3.0	2.0
(*) My hands got in the way of showing things to my partner	1.0	2.0
The camera focused on what I wanted to show (VC only)	N/A	2.0

Table 2. Post-task questionnaire medians of 5-point Likert scale ranging from strongly disagree (0) to strongly agree (4).
(*) indicates significant difference by Wilcoxon signed-rank test ($p < 0.05$)

influence the participants' behavior or handling of the prosthetics. We informed participants of the collaborator's protocol prior to asking questions and presenting the prosthetics.

In the face-to-face condition, the collaborator sat directly across a table from the participant (see Figure 1). In the video conferencing condition, the participant communicated with the collaborator via Google Hangouts running on a laptop at the table (see Figure 2 for screen layout). The participant and the collaborator sat in the same room, facing away from each other; participants could only see their collaborator through video chat, but could hear each other through ambient audio.

For all participants, we maintained the same ordering for hand comparisons (First pair: Cyborg Beast and Raptor Hand; Second pair: Raptor Reloaded and Phoenix Hand). This consistently presents the prosthetics in chronological order, such that the participant is always comparing a new pair of hands that represents a distinct evolution in the prosthetic hand designs.

Finally, after completing both conditions, participants responded to a questionnaire asking them to describe any difficulties they had in each condition, and rate their attitudes towards communication in each condition along a 5-point Likert scale (e.g., *"How much do you agree with the following: I knew what my partner was looking at most of the time"*. See Table 2 for list of questions). While no time limit was enforced, each participant completed the study in under one hour.

Figure 2. (Top) The view that the participant sees on their computer. The small bottom right corner shows a preview window of the participant's camera. (Bottom) The view on the collaborator's screen. The small bottom right corner shows a preview window of the researcher.

Participants

We recruited 20 participants—eight male, twelve female, aged 19-58 (mean=28.6 years)—through poster ads on our university campus and email lists. We emphasized that no technical experience was necessary to participate. Each participant received $20 CAD remuneration.

Four participants worked at the university in various administrative positions while the rest were students in a variety of university departments. Only one participant had previous experience with prosthetic limbs. All participants indicated experience with video conferencing software; two "daily" users, six that use video conferencing "several times a week", two "once a week" users and ten "less than once a week" users.

Data Capture and Analysis

We used three sources to collect video footage during our study; an over-the-desk Canon Vixia HFS10 camcorder, a Logitech C920 HD webcam mounted on the participant's laptop (VC), and the built-in webcam on the collaborator's laptop (VC). An example of the screen layout from the participant's view can be seen in in the top image of Figure 2.

We followed an iterative review of videos and transcribed selected specific full videos and portions of videos described by Jordan and Henderson for interaction analysis [31]. We reviewed all participant videos and noted communication behaviors that differed between the face-to-face condition and the video conferencing condition. We also measured the duration of answers to each researcher question, as well as the duration of participants focus of attention (prosthetics or partner/screen). We tagged participant utterances of problems or issues they found in the prosthetics, and instances where participants narrated their actions. Our analysis focuses on participants' responses to the structured critique questions which asked for a comparison of the models, and review of comfort, usability, and performance.

FINDINGS

"Material shapes our ways of doing" [23], and indeed it shaped how our participants formed and communicated critique. We first discuss three elements that formed their prototype critique,

Time	Verbal	Action
01:28	***In the portion that goes over the arm, any differences that you notice there?***	
01:31	*Well there's this part, for the wrist, or the hand.* *In terms of the two strap versus the one strap* *I don't know if there would be too much of a difference functionally between the two* *I mean with two straps*	Looks down
01:51	*twice the chance that*	Looks up
01:53	*one could break.* *Does give you more flexibility for clothing or fabric...*	Looks down

Figure 3. (Left) P16 (F2F) with their attention focused down at the prosthetics as they inspect the straps. (Right) Selected transcript from P16, when comparing each prosthetic. While the entire response takes 36 seconds, they only switch attention from the prosthetics to the researcher for two seconds.

and participants' general interactions with the prototypes. We then describe how participants used their own actions and embodiment to show subjective experiences. Finally, we unpack participants' difficulties in visually communicating a predominantly 'invisible' material experience.

Communicating about and with Prototypes

Through a series of comparisons, our participants' goal was to evaluate and critique pairs of prototypes. Three elements repeatedly surfaced to support their critiques:

Physical Detail. Particularly during the video conferencing condition, participants described differences between small details or tactile features, such as the roughness or surface texture of the 3D printed prototype. For example, P10(VC) verbally detailed the location and function of clear elastics used in the finger joints of the white hand, which are difficult to see on camera (see Table 3). This detail was then compared to a more visible set of black elastics on the orange hand.

Prototype Behavior. In their comparisons, participants communicated how the prototype behaved or reacted, including: force on the wrist needed to close the hand (P2, P5, P8), elastic tension resisting hand closure (P5, P8, P13), grip strength based on friction (P2, P4, P8), string strength and how they might break under tension or repeated use (P3, P10), stability of the prosthetic when worn (P10, P16), and potential strength of the plastic to withstand use (P1, P3, P5, P13). All of these behaviors correspond to how a particular element of the design would respond to a particular use case.

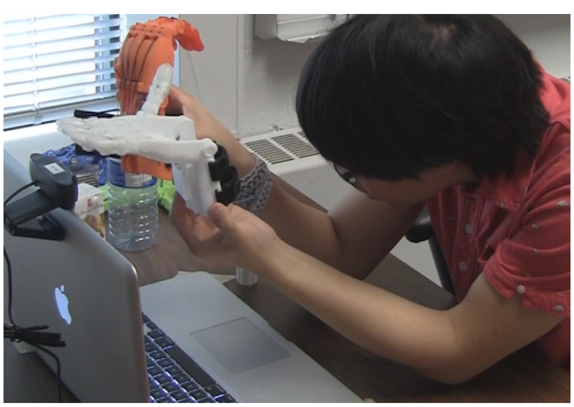


Figure 4. P2(VC) while communicating, holds up two e-NABLE prosthetic hands close to the camera.

Personal Experience. In addition to recounting prototype behavior, participants also described their own subjective experiences in using the objects—their role in physically operating the prototype. For example, P18(VC) describes the force needed to push on the back of the prosthetic to close the hand: *"...I push and it seems to be a little bit harder. But it still goes. But, I have to push harder."* In this case, P18 recounts both their own action—where and how much force they applied to the back of the hand—and the prototype's reaction—how the prosthetic resisted force yet eventually closed. The participant must personally experience the amount of effort needed to actuate each prototype, and verbally articulate this difference.

All participants in both conditions dedicated most of their visual attention on the physical prototypes under consideration, looking for details, behaviors, and experiences to construct their critique. Participants only lifted their gaze occasionally to look at their collaborator (F2F) or the video connection (VC), and then they quickly look back down to the prototype. For example, in a 36 second response comparing the gauntlets (where the wearer places their arm) of each prosthetic design, P16 (F2F) spent only two seconds looking up at their collaborator (see Figure 3). The rest of the time they spent focused and engaging with the prosthetics. This is consistent with past research on socialization in the presence of an alternative visual focus (e.g., social television [12]).

Participants' hands were preoccupied with the prototypes themselves. Our participants performed both *epistemic actions*—actions used to discover information [33] to understand how the prototypes worked and *pragmatic actions*—actions that "brings one physically closer to a goal" [33]—to demonstrate or show the prototype. Epistemic action often alternated with pragmatic action. For example, when showing details of the fingertips, P2 first picked up both prototypes to examine them, then brought the prosthetics towards the camera to offer

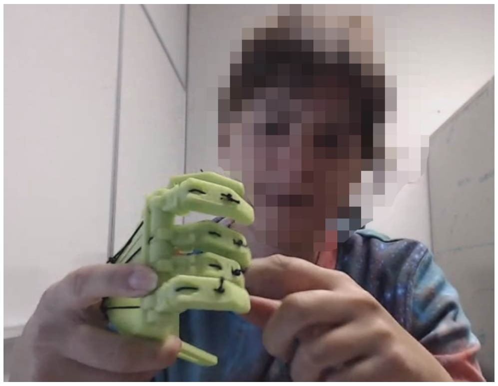


Figure 5. P5(VC) shows how the prosthetic behaves, discussing string tension and joints. ***"If I'm closing this one and I touch it like this, they kind of bounce around a bit."***

their collaborator a better view (Figure 4), and finally resumed individually examining the hands.

However, throughout the critiques participants were simultaneously understanding and communicating physical details, prototype behaviors, and their user experience. For example, P5(VC) (see Figure 5) wanted their collaborator to see how the hand reacts to them touching the fingers, trying to understand if the behavior was the result of tension of the actuating strings or friction in the joints: *"If I'm closing this one and I touch it like this they kind of bounce around a bit."*

Over the course of their continuous concentration on and interaction with the prototypes, participants developed an understanding of how the prototypes feel, function, and compare.

Subjective Experience

As subjective experience is a key element of critique, participants inevitably brought their own actions and embodiment to the critique. Here we discuss two ways in which participants

Time	*Verbal*	*Action*
05:57	*It's white on white but...*	Holds up white hand to camera
06:03	*...to this part*	Points to white finger tip
06:12	*It would be here.*	Puts down prosthetic, points to P10's own finger
06:20	*You can see the black here, that's bending*	Shows black elastic on orange hand
06:24	*That bending is facilitated here,*	Picks up white hand
06:29	*but it's white on white, so you can't see it.*	Holds up white hand to camera

Table 3. P10(VC) holds up prototypes to the camera, gestures to prototypes on-camera, and references their own physical geometry to describe the precise location of elastics on a prosthetic hand.

Figure 6. P14(VC) explains the actions users of the prosthetic would do to close and open the hand by performing an up and down motion with their own hand as surrogate.*"When they press down their palm like this."*

inserted themselves into the critique: self-narrating actions, and using their body as a surrogate for prototype behavior.

Narrating Actions in First Person

Both in the face-to-face (10 people) and in the video conferencing condition (13 people), participants narrated their actions to their collaborator in the first person. Participants used themselves as the *deictic centre* [24]—using the first-person "I", and describing how the prototype behaved in response to and in reference to their own actions. While self-narration occurred in the face-to-face condition (34 instances, 10 people), it happened more frequently during the video conferencing condition (92 instances, 13 people). In the video conferencing condition, self-narration occurred for both on- and off-camera actions. The actions our participants described included: grasping objects (P2, P4, P10, P14), lifting objects (P2, P4, P7, P10, P13), mimicking the closing of the prosthetics (P5, P6, P7, P14), or vigorously shaking the prosthetics (P14). This self-narration often occurred simultaneously with the action itself. For example, P14(VC) describes waving the prosthetic hands, as she waves them (Table 4).

Participants also chose to describe off-camera action instead of bringing that action into view. In several instances, P14(VC) narrates off-camera actions—describing their arm resting on the edge of the table, or rotating their forearm.

Embodied Communication

Fifteen participants used their own body as a surrogate for the prosthetic hand or to simulate usage. For example, P14(VC) used their hand to demonstrate how the fingers of the prosthetic react when the wearer bends their wrist (see Figure 6).

Participants' natural hands share similar joints and features as prosthetics, and are located where a user would wear a prosthetic. Thanks to proprioception, their own hands are easy to spatially manipulate [39] and make for a particularly good surrogate for this conversation. While using one's own body is easier when imitating prosthetics, we believe similar types of embodied communication may appear when discussing object's mechanical functions that can be mimicked by human physiology (e.g., showing a hinge by bending the wrist, showing the motion in a ball joint by rotating the shoulder). We also believe that embodied actions could be used to show how

Time	Verbal	Action
02:11	*So if I'm waving it, not so much is happening.*	Waving white prosthetic
02:14	*If I'm waving it, a whole bunch is happening.*	Waving orange prosthetic
02:23	*If I'm moving my wrist my hands don't necessarily move...*	Waving own wrist
11:15	*Let's say I just have my hand and I'm resting it on a table.*	Resting hand on table off-camera
11:20	*I have to turn my whole forearm kind of off to the side.*	Rotating hand and forearm off-camera

Table 4. Transcript of P14(VC), self-narrating as they wave hands, and compare against their own hand

imaginary wearable technology (e.g., smart watches, eTextiles) would interact with the wearer's anatomy.

Because the prosthetics were designed to replace a natural hand, participants also compared the prosthetic's form and function to their own hand, to decide which designs more closely resembled real-world anatomy. In the earlier example, P14(VC) compared how the fingers on each prosthetic hand moved when waving the hand, and then compared how their own fingers behaved while waving their own wrist (Table 4).

Remote Difficulty: What is Visible?

We observed our participants having difficulties throughout their critique, primarily around the core misunderstanding of what aspects of their critique are visible at a given moment. During face-to-face conversations, participants may assume the collaborator can perceive more cues about the object's detail (e.g., stereoscopic view of form, hearing subtle creaks). P18(F2F) became self-aware that they were presenting with less detail than during the video conferencing condition: *"I'm, like, just describing less detail than when we are video conferencing. Because, I'm assuming you can see everything."*

Participants indicated in our questionnaire that in the remote condition they were not able to show their collaborator what they intended, knew less about where the collaborator was looking, and felt their hands may have gotten in the way of showing things (Table 2). All of these concerns highlight a key challenge of video-mediated critique: an awareness of what the audience can and cannot see in a scene. In the following subsections we discuss how our participants struggled with the questions: (a) *what is captured?* (b) *where is my collaborator looking?* and (c) *who is responsible for visibility?*

What is captured?

In our questionnaire, five participants (P4, P10, P12, P13, P19) specified that they had difficulty ensuring that the views they wanted to share with their collaborator were in frame. Johnson et al. showed in prior research that in the context of robot teleoperation that field of view can affect collaborative tasks [29] and our findings support this in the scenario of a design critique. In practice, objects can be out of frame intentionally (during epistemic action) or unintentionally. For

Figure 7. P3(VC) inspects and compares the prosthetics, holding them such that the majority of the prosthetics are not visible due to occlusion from P3's hands and foreshortening.

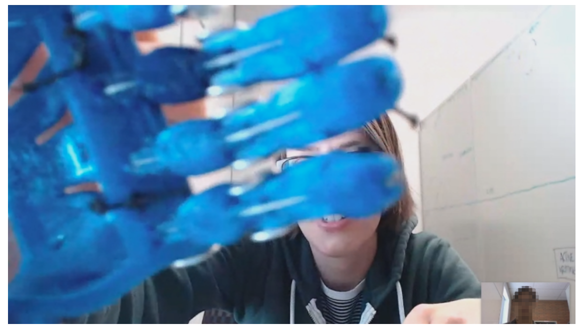


Figure 8. P18(VC) holds the blue prosthetic hand close to the camera in an attempt to show details of the fingertips. Unfortunately, the webcam remains focused on the P18; the image of the prosthetic is blurry to the viewer. *"I don't know if you can see the surface texture."*

example, P12(VC) held the prosthetic too low to be in the camera view, and remarked, *"Ah, I don't know where the camera is,"* before readjusting their position and lifting the hand back into frame.

Unfortunately, participants were also unaware when their own hands were in frame and occluding their collaborator's view of the prototypes. One participant (P7) explicitly commented on this difficulty in the short answer portion of the questionnaire, six participants "agreed", and two "strongly agreed" that their hands got in the way. In Figure 7, P3(VC) handles the prototypes such that the majority of the prosthetics cannot be seen on camera. While the prototype is in frame, it is oriented to support P3's own point of view. P3's hands are also in frame, blocking the camera's view of some of the prototype. P3(VC) manipulates the prototypes in an epistemic action before returning to a pragmatic action to intentionally show particular views to their collaborator.

Even once the prototype is in the camera's field of view, participants were still unsure if details were in focus. Because the camera automatically focuses, it can be difficult to predict whether or not an object held close to the camera (to make its details larger) is actually within focus. In the questionnaire, three participants (P10, P11, P18) indicated difficulty knowing or managing what was in focus. In Figure 8, P18(VC) holds the prosthetic extremely close to the camera, in an attempt to show that the surface of the fingertips are made up of small plastic bumps. However, the camera's focal distance is calibrated for someone sitting several feet away, not for objects inches away from the camera. The resulting close-up of the prosthetic is very blurry. Unfortunately, P18 cannot tell that this image is blurry, as the preview window for the participant to see themselves is too small. During the exchange, P18(VC) says, *"I don't know if you can see the surface texture."* Once again, the size and format of standard video conferencing does not help people understand what is readily visible.

Where is my collaborator looking?

In our questionnaire, three participants (P10, P13, P16) were concerned that they could not tell where their collaborator was looking during the remote communication condition. For example, P16 wrote, *"Flustered, can't see if their eyes are looking at exactly what I want them to."* Furthermore, seven participants (P4, P6, P11, P12, P13, P14, P18) indicated not knowing what their collaborator was looking at during video communication (ie. Likert response of *Disagree*) as well as one (P10) response of *Strongy Disagree*. Comparatively, when considering the face-to-face condition only three participants (P7, P14, P20) acknowledged a lack of awareness to where their collaborator was looking (ie. Likert response of *Disagree*). Past research has found that gaze awareness can help collaborators see what is currently of interest during tasks [25]. In our scenario, understanding where a collaborator is fixated may have helped the participant gear their critique towards areas in view that the collaborator is interested in. However, in the context of a critique with multiple audience members this solution may not scale well.

It is possible that participants were peripherally aware of cues from their face-to-face collaborator that could not be seen over the video-link. However, given participants' physical (visual and tactile) engagement on the prototypes, they may not have been aware of such cues during either condition. This resonates with past work highlighting the importance of gaze awareness in remote physical tasks [19, 1].

Who is responsible for visibility?

Not all participants consistently showed the prototypes to their collaborator as part of their communication. In our questionnaire, four people (P2, P10, P11, P12) mentioned having difficulty "remembering" to show the prototypes to their collaborator during the video condition. One possible reason participants felt that *"forgetting to present"* was a problem is that they felt responsible for their collaborator's video view. Prior research [46] has also discussed collaborators taking on responsibility to manage experience during a "remotely shared meal" or while "visiting a new place together" to entertain other participants. Our findings support the presenter's responsibility for the view; however, when forming their critique and engaged in epistemic action—intensely focusing on their material experience with the prototypes—participants had difficulty remembering this responsibility.

One alternative to this model is for the collaborator to take some responsibility for their own view. In our particular study protocol, the collaborator was not allowed to comment on how the participant chose to use the video conferencing setup. It seems at first that this protocol would be too constraining—putting all the responsibility on the person giving critique—but as described in our motivating scenario this is actually reflective of the real video conferencing environment in open-hardware groups. Show-and-tell feedback and critique is given with generally little interruption from the audience.

The same four participants who had difficulty remembering to show the prototype (P2, P10, P11, P12) along with an additional participant (P20) suggested that their collaborator could be responsible for correcting the presenter when objects are out of view. Past research in HCI has offered ways for remote participants to independently or semi-independently control their the view (e.g., robotic telepresence [46], drone camera [30]). However, it may be difficult to scale these solutions up to scenarios with a large audience of collaborators.

IMPLICATIONS FOR DESIGN

Our findings highlight some of the interesting strategies and difficulties that our participants encountered while giving prototype critique via video conferencing. Many of our methodological choices offer perspective of how to go about studying critique—structuring conversations, focusing on features or qualities that are not readily visible, and reviewing complex objects. Our primary goal in observing these sessions is to inform the development of new collaboration tools for remote critique and user feedback. Here we discuss some key factors that should be considered in the development of remote communication systems for remote critique. While we provide specific examples of how we envision future systems,we consider the discussed implications as *strong concepts* [27], "solution-oriented pieces of generative knowledge [...] between instances and theories", that are applicable to remote critique as well as other forms of video communication of materiality.

Build Visual Context around Material Experience. Because people are visually focused on the objects in their hands, their gaze is more often directed downwards rather than up towards a vertical display. While traditional media spaces assume an upwards gaze, collaboration systems for physical prototype critique should build around the material exploration of objects as the center of the user's focus. For example, head-mounted displays [18] or interactive tabletops would allow the reviewer to keep the media space in their peripheral vision while their focus remains downward towards the object in their hands.

Provide a "Detail" View. Our reviewers brought objects towards the camera when they wanted to highlight physical details (e.g., small features, textures). This does not necessarily result in an effective view; it requires the reviewer to hold up the prototype, position interesting details towards the camera (and away from them), and hope that the forward-facing webcam will properly focus on the close-up object. Systems supporting remote critique need to offer an effective means of close-up communication—potentially as a dedicated view that does not overlap with a "talking heads" overview. Several existing off-the-shelf technical solutions may offer better close-up video capture. For instance, USB endoscopes, used by plumbers to examine blockages in pipes, have a short focal distance for objects very close to the lens. Whereas a "talking heads" camera provides a "context" view, a dedicated "detail" or "focus" view could be presented as an additional or alternative view in a video conference; reviewers could manipulate a secondary camera, as needed, to provide detail. Introducing this extra view does come with a cost, as discussed by Gaver et al. [22]—presenters must manage and the audience must follow multiple fragmented views. However, as a trade-off these specialized close-up views can make a participant's otherwise 'invisible' material experience of small physical details now visible, relieving the presenter of detailed verbal description.

Prioritize Camera Preview. When performing pragmatic actions—controlling how feedback and critique are shared—our participants composed the view on the video feed. Our participants had difficulty viewing the camera preview window because it was so small, and was usually obstructed by the hands and objects held up to the camera. We recommend that systems for remote critique place camera previews in line with the presenter's view of the prototype itself. In this setup, both the camera and the presenter share a similar view of object details. One possible solution to address this is a life-size presenter preview. Existing research on life-size displays for collaboration such as the *t-room* [54] explore how collaborators can be represented in large life-size panels. We imagine a similar tabletop system that could allow the presenter see both themselves and their collaborators. The presenter could then clearly preview the composition of the camera view during their presentation without blocking their view of the prototype.

Leverage Pragmatic Action as Documentation. When switching to pragmatic interaction with the prototypes, participants brought objects into the camera's visual frame and focus to highlight key aspects of the object's design. In some ways, video conferencing results in more clearly articulated and explicitly expressed feedback than the face-to-face condition [26]. Recordings from the audio and visual channels from this type of video conference could be reused in project design documentation. One example of short-term reuse could be to convert live video demonstrations into a looping GIF, an external representation. The reviewer can then refer back to an 'authored' demonstration without need to continuously manage the camera view or operate the prototype. This type of system could be algorithmically controlled (similar to that proposed by Ranjan et al. [47]) and triggered to automatically create recordings when the presenter intentionally engages the camera by bringing the prototype into closer proximity. For example, this proximity recording could be engaged when the presenter demonstrates grasping with the prosthetic hand (bringing the prosthetic in close to the camera to emphasize the grips of the fingers) and the recording would stop once the action moves away from the camera. Once this recording is created the presenter could play back the video for themselves and the audience for reference as they discuss the prosthetic, no longer burdened by simultaneously handling the objects and managing the camera view.

LIMITATIONS

We chose prosthetic hands for our study because their relative complexity led to rich critiques in the e-NABLE community. However, the scale and complexity of physical tasks changes how people communicate and the value of specific forms of telepresence (e.g., robotic telepresence [46], augmented reality [45]). As we found in our pilot studies, object complexity affects the amount of detail and nuance in critique—increasingly complex objects may affect the strategies presenters use to communicate longer more complex critique.

Only one participant (P11) had previous experience with prosthetics. Our novice participants had very few comments about assembly or print quality. While novice reviewers have valuable input, they also require more time to familiarize themselves with the prototype. Domain experts or veteran users may use alternate communication strategies, have different priorities, or focus on different types of features. Furthermore, we elicited critique that reflects the "casual" communication that we observed in open-source hardware communities, as opposed to formal design critiques found in design schools or companies. Future work could look at the effect of remote communication on formal critiques (e.g., [9, 8]).

Participants in the study were aware that their remote partner was also one of the researchers. Therefore, they may have assumed that the researcher was already familiar with the prosthetics used in the study. This perceived difference in expertise may have led participants to refrain from mentioning details of the prototypes that they expected the collaborator to already know about. Using a second participant as the collaborator would let us look at how critique might be co-constructed. Our study protocol also limited how the collaborator was allowed to participate—this reduced the amount of back-and-forth dialogue, and did not necessarily take into account the perspective of the person listening to the remote critique. Future studies that include more natural dialogue would be able to account for both sides of the communication.

CONCLUSIONS AND FUTURE WORK

Our observational lab study brings new insight on the ways people communicate—and the challenges they encounter—as they critique pairs of physical prototypes for both face-to-face and video conferencing audiences. Each participant was given two sets of prosthetic hands to compare and critique for a collaborator. We analyzed how participants handled, assessed, and articulated their critiques of complex physical prototypes. In both conditions our participants centered their attention on their material experiences with physical prototypes under review, not the visual view of their collaborator. However, this led to difficulties in the video conferencing condition, as participants had difficulty staying aware of what was visible to their collaborator. We offer several design implications for how collaborative systems can alleviate these difficulties and better support remote physical prototype critique.

3D printing and other low-cost manufacturing techniques are increasingly present in people's lives. As a result, more people will need critical discussions around physical prototypes to share expertise and offer feedback on each others' designs at a distance. Our findings on video-mediated critique inform how new technologies can help reviewers effectively share their opinions and hands-on experiences with the physical objects they create and use. We look forward to future work that continues to explore new configurations for remote critique.

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