# IllumiShare: Sharing Any Surface

**Sasa Junuzovic, Kori Inkpen, Tom Blank, and Anoop Gupta**
Microsoft Research
One Microsoft Way, Redmond, WA 98052
{sasajun, kori, tomblank, anoop}@microsoft.com

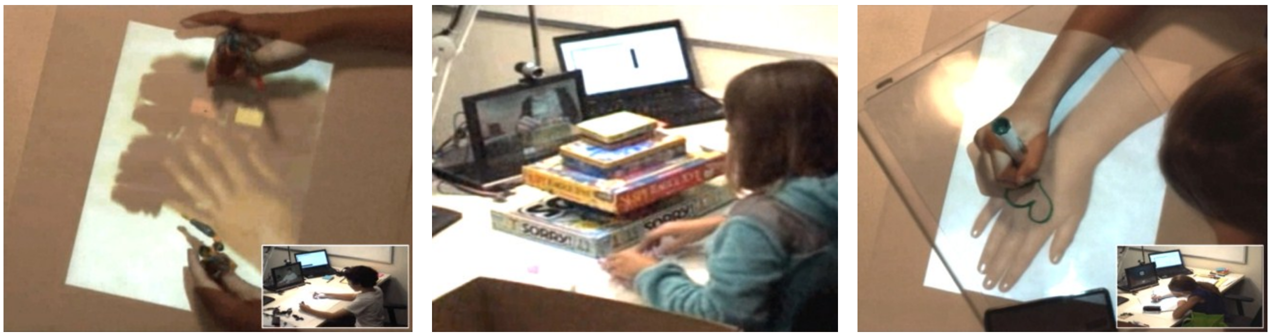

**Figure 1. Remote play with (left) person and task-reference spaces, (center) only person, and (right) only task-reference space.**

## ABSTRACT
Task and reference spaces are important communication channels for remote collaboration. However, all existing systems for sharing these spaces have an inherent weakness: they cannot share arbitrary physical and digital objects on arbitrary surfaces. We present IllumiShare, a new cost-effective, light-weight device that solves this issue. It both shares physical and digital objects on arbitrary surfaces and provides rich referential awareness. To evaluate IllumiShare, we studied pairs of children playing remotely. They used IllumiShare to share the task-reference space and Skype Video to share the person space. The study results show that IllumiShare shared the play space in a natural and seamless way. We also found that children preferred having both spaces compared to having only one. Moreover, we found that removing the task-reference space caused stronger negative disruptions to the play task and engagement level than removing the person space. Similarly, we found that adding the task-reference space resulted in stronger positive disruptions.

### Author Keywords
Telepresence; person, task, reference spaces; video; surface sharing; video echo cancellation; children; remote play.

### ACM Classification Keywords
H.4.3 [Information System Applications]: Communication Applications – Computer conferencing, teleconferencing, and videoconferencing.



### General Terms
Design, Experimentation.

## INTRODUCTION
Three important channels of communication for people working together across distance are person, task, and reference spaces [2]. Person space provides information about the remote collaborator such as facial expressions and gestures. Task space establishes a shared work area in which collaborators work together. Reference space can be considered an intersection of person and task spaces as it provides awareness of the collaborators in the shared workspace. While all of them are important, our focus is on task and reference spaces.

There have been many systems created for sharing task and reference spaces [4,8,11]. While all of them are beneficial to remote collaboration, all of them also have an important inherent weakness: none of them support sharing arbitrary physical and digital objects on arbitrary surfaces. Therefore, the degree to which they can provide natural and seamless interaction is limited. Consider a common scenario where two people are sketching together on a piece of paper using colored pens. While all existing systems support shared drawing, they do not do so naturally or seamlessly because they either require the use of a computer or a special non-paper surface or they support only grayscale images.

We present a new peripheral device, called IllumiShare, for task-reference space sharing that solves the inherent weakness of existing devices. It is a device that shares arbitrary physical and digital objects on arbitrary surfaces and provides rich referential awareness. It is both cost-effective and light-weight. It uses of a low-cost camera, a low-cost 60Hz pocket-size projector, and a hardware chip that synchronizes them in a way that removes visual echo without flicker. It resembles a desk lamp (see Figure 2), and like a desk lamp lights up a surface simply by being pointed at one, IllumiShare shares a surface.

One of the strengths of IllumiShare is its simple affordance – anything in the lit up area is shared with others. For example, with IllumiShare, remote collaborators can draw together on a piece of paper by placing the paper in the lit up area. They can draw together right on the paper and also see each other's hands as they point at parts of the drawing.

The goal of this work was to evaluate whether IllumiShare supports natural and seamless remote interactions. Generally, we were interested in the answers to the following questions regarding IllumiShare:

- Can people understand its sharing metaphor?
- Does it encourage natural interaction?
- What value does it add over having only video of the remote people (person space)?
- When it is being used, how important is the video of the remote people (person space)?

To get a better understanding of these questions, we studied pairs of children in unstructured remote play. Prior work has shown that children are able to transcend the video medium and are comfortable interacting with video [1]. They are also comfortable interacting with loved-ones in virtual environments that show their videos and pictures [3,7]. Previous research has also demonstrated that shared surface systems are beneficial for supporting children's interactions both with loved-ones [12] and friends [13]. Given these findings, we were interested in the answers to the following specific instances of our general questions in the context of children's remote play:

- Can children understand its sharing metaphor?
- Does it encourage children to play similar games as those they play face to face?
- What play tasks supported with IllumiShare fall apart when kids only have each other's videos?
- What play tasks are supported best with both IllumiShare and video?

To summarize, the main contributions of this paper are twofold. First, we present a new surface sharing technology called IllumiShare that shares the task-reference space better than prior systems. Second, we describe a study of children's use of IllumiShare and explore the importance of the person and task-reference spaces during remote play.

The rest of this paper is organized as follows. First, we describe IllumiShare. Then, we discuss prior studies of remote interactions involving children. We then present our study and its results. Next, we discuss IllumiShare limitations and its applicability beyond a lab study. We end with conclusions and directions for future work.

## SHARING ARBITRARY SURFACES

In this section, we describe a new system we developed that enables an arbitrary surface (e.g., table, whiteboard, etc.) to be shared among remote participants. This system provides remote collaborators with both a shared task space and a shared reference space. We had three main design goals:

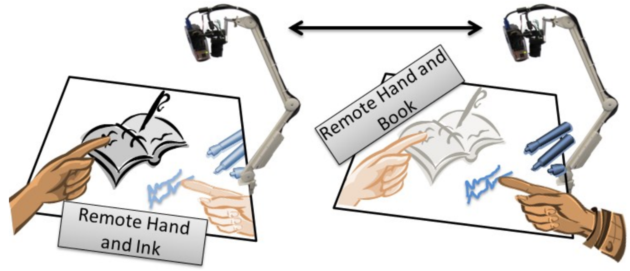


**Figure 2. Illustration of regular table sharing with IllumiShare. Photos of the actual device are shown.**

- Share arbitrary surfaces and objects
- Provide rich referential awareness
- Cost-effective, light-weight form factor

### Prior Surface Sharing Systems

An important question when sharing a surface between remote locations is whether the surface is arbitrary or specialized. Generally, sharing a specialized surface is easier than sharing an arbitrary surface because the surface properties are controlled. Several systems have been developed that shared specialized surfaces, such as ClearBoard [4], Commune [6], and others. Sharing arbitrary surfaces, on the other hand, makes the system more flexible as it can be used anywhere, which is the approach we take.

Another important question is whether physical objects, such as hands and real pen and paper, can be shared. Sharing only digital objects is easier than sharing physical objects since digital objects only need to be displayed while physical objects must be captured first and then displayed. Some digital surface sharing systems allow limited sharing of physical objects. For instance, the VideoArms [9] system shares users' hands but not arbitrary physical objects. We focus on sharing arbitrary digital and physical objects.

Surface sharing systems that aim to share any surface and object on it typically use a camera-projector pair at each site. The camera captures video of the local site, and this video is projected by the projector at the remote site.

One of the key challenges of surface sharing systems based on camera-projector pairs is the problem of *visual echo* (or *visual feedback*). Visual echo results because a video loop is established between sites. The loop occurs because the projected video from a remote site is captured locally and sent back to the remote site. The resulting re-projection of captured video leads to visual duplicates of the artifacts on the surface. Although Wellner showed in his Double Digital Desk [10] that it is possible to reduce visual echo to only a few frames by controlling ambient lighting and projection contrast, in general, the duplicate images make it difficult to use the system, especially when hands and artifacts move across the shared surface. Therefore, visual echo should be removed entirely. There are several ways to remove visual echo. As the rest of this section describes, the choice of solution impacts the sharing capabilities of the system.

One visual echo removal solution is to remove the projected image from the image captured by the camera in software. Such an approach was described be Liao et al. [5]. They require an initial calibration of projector and camera that is sensitive with respect to ambient light levels at the surface. Since ambient light levels at the surface change as people use the surface (e.g., they lean in or out, place objects on the surface, etc.), this approach is not practical.

An optical alternative to the software solution that is not sensitive to changes in the ambient light is to use polarized isolation between the camera and the projected image or projection source. With this approach, the light reaching the camera does not include any of the light showing the projected image. Thus, the camera does not see what the projector is showing, which breaks the video loop between sites and removes visual echo. Examples of these systems are Tang's and Minneman's VideoDraw [8] and Yarosh et al.'s Share Table [12]. The main drawback of polarized isolation approaches is that only surfaces and objects whose material preserves polarity can be used. Everyday surfaces and objects such as a table, a piece of paper, or a toy do not necessarily have this property, so they often cannot be used.

An alternative optical solution that does not require a special surface is to separate the light frequencies used by the projector and observed by the camera. Since image projectors throw only light in the visible space, placing an IR-pass filter in front of the camera will prevent the projected image from interfering with the image captured by the camera. As many objects reflect IR light, the camera can still capture them. This solution was first used in Wilson's and Robbins' Playtogether system [11] and was also utilized by Yarosh et al. [13]. Unfortunately, this approach provides only grayscale images of the shared surface. Also, objects with low IR reflectivity cannot be captured, and objects with similar IR reflectivity appear as a single object when placed side by side.

A third optical visual echo removal solution that is actually able to share arbitrary objects and surfaces is to separate the camera and the projector in time – turn the projector off when the camera is on and vice versa. This time multiplexing must happen at 60Hz; otherwise, the projected image will flicker noticeably. With a 120Hz projector, the projector can simply be turned off every other frame. However, 120Hz projectors are large and heavy. Therefore, the physical infrastructure to hold them suspended above a surface is also large. They are also costly. Hence, a 120Hz projector would not meet our cost-effective and light-weight design requirement. To meet this design goal, the projector should be a pocket-size projector or smaller. Unfortunately, all current projectors that meet the size criteria are 60Hz, which means that the approach of turning them off every other frame will result in visible flicker.

To summarize, the visual echo solutions described earlier use software, polarized isolation, light frequency multiplexing, or time multiplexing between the camera and the projector. The software solution is not robust and neither frequency multiplexing nor polarized isolation work across arbitrary surfaces and objects, leaving only the time multiplexing approach as viable. The challenge was finding an approach that worked on a 60Hz low-cost projector, did not produce visible flicker, and was simple to build. We describe our solution next.

### IllumiShare

Our time multiplexed solution uses an Acer K11 200 lumen 60Hz DLP style projector utilizing RGB LED light sources and a Point Grey 1.3MP Color Chameleon camera with a global shutter utilizing an external trigger.

In our design, we turn off the LED projector illumination for a short period of time and take the picture with the camera during the illumination off time. To prevent flicker in the projected image, we do this at a 60Hz rate. Figure 3 illustrates an example RGB projector LED timing diagram where each LED is on for an interval of time that provides proper color balance based on the efficiency of each LED. Note that the blue LED is on for a shorter time because a typical blue LED is more efficient than either a red or green LED. Figure 4 illustrates an example of stealing time for

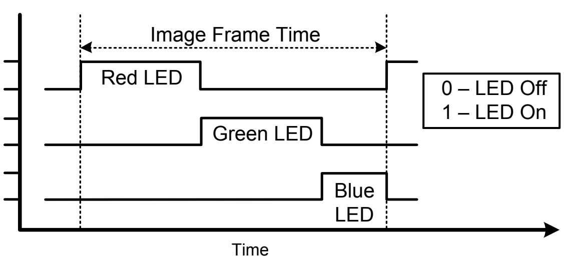


**Figure 3. An example RGB LED on-time during a frame.**

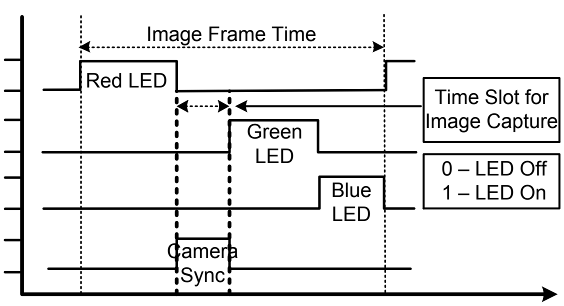


**Figure 4. An example camera capture time slot during a frame where the red and green LEDs are briefly turned off.**

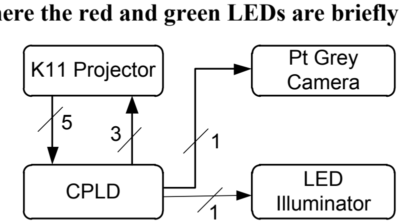


**Figure 5. Block diagram of IllumiShare system components.**

camera capture from the red and green LEDs. For other projectors with different illumination approaches, this basic concept can still be used. For example, a projector using a single white LED illuminator simply needs to be turned off for the capture time. Alternatively, some RGB projector systems, like the Acer K11 we used, have five subfields (3.33 ms) for each 60Hz frame where each subfield has a waveform similar to Figure 3. In this case (as in our actual hardware), we turn off the LEDs during the first two subfields (6.67ms) and use that time for image capture. The hardware chip that performs the synchronization is simple. Figure 5 shows the system block diagram with all components. The key observation is that there are only 8 wires that connect to the projector (3 RGB controls, 3 RGB drivers, frame sync, and ground). The CPLD logic simply generates the waveforms such as those in Figure 4 from the input waveforms such as those in Figure 3.

One issue in turning the projector LEDs off for a period of time is that it can affect the color balance of the projected image. The reason is that the RGB LED sources are not all on at the same time. Instead, as shown in Figure 3, only one of the LEDs is on at one point in time. To preserve the color balance, the amount of time stolen from each LED light must be proportionate to the time the LED is on during a frame. As mentioned above, the Acer K11 projector has five subfields for each frame, and each subfield has the same RGB LED waveform. By turning off Acer K11 projector for the first two subfields in each frame, we ensure that the color balance is preserved.

Another important issue when time multiplexing the camera and the projector is to ensure that the camera gets a sufficient amount of light during exposure time to capture a good image. In our 60Hz (16.67ms) system, we stole 6.67ms for the camera capture time, which is a relatively short camera exposure time. It is possible to use the maximum camera gain to get reasonable exposures using conventional room lighting during such short time frames. However, this adds noise to the image, which is not desirable. Instead, we use an alternative solution in which we add a white LED illumination source that only turns on while the camera is capturing the image. As a result, the additional illumination improves lighting during camera exposure time without washing out the projected image.

### Digital Sharing and Multi-Way IllumiShare Scenarios

So far, we have focused on how IllumiShare can share arbitrary physical objects on two arbitrary physical surfaces. It also shares arbitrary digital objects because these objects can be displayed by the projector. IllumiShare also supports sharing (a) both physical and digital objects, (b) among multiple sites, and (c) with arbitrary end points.

An important issue when sharing digital objects is how the image of the digital object and the video of the remote site are displayed at the same time. Superimposing them does not work because the local user will see either the digital object or the image of the remote surface, but not both. A simple solution is to add transparency to one or both images and then superimpose them. However, in our experience, this approach did not work well. An alternative, shown in Figure 6, is to superimpose only the foreground from the remote site on top of the digital objects. The foreground includes user's hands, ink, and other physical objects on the surface but not the surface itself. Thus, the foreground from the remote surface does not obscure the digital image. This requires foreground-background separation of the captured image, which IllumiShare does in software.

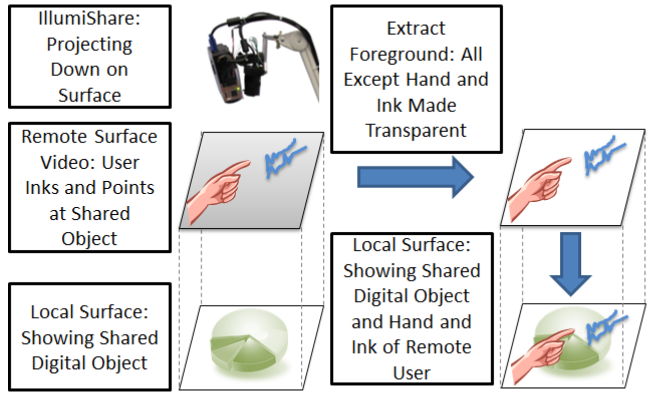


**Figure 6. Digital object sharing with IllumiShare. Foreground of remote surface is layered on top of shared digital objects.**

A related issue occurs when sharing surfaces from more than two sites because images of multiple remote surfaces must be displayed simultaneously. In this case, IllumiShare again shows only the foregrounds of each remote surface. Unfortunately, the foregrounds of remote videos can still occlude each other if multiple remote users place physical objects in the same location. It is up to the users to detect this and resolve it using social protocols if it is a problem.

Finally, IllumiShare can share an arbitrary surface with a user without an IllumiShare, such as a laptop or tablet user. This scenario is similar to sharing a digital object since the non-IllumiShare user can share digital objects only. In this case, that user sees the surface foreground from the IllumiShare user superimposed on the digital objects. Although the shared task-reference space is asymmetric in such scenarios, it is useful to support them to enable some IllumiShare features when not all users have the device.

### IllmiShare Setup

To share a surface using IllumiShare, several setup steps must be performed. First, the projector and the camera need to be focused. They currently have manual focus lens, so the user has to focus them. This could be automated by using auto-focus lens and/or laser projectors which are always in focus. Next, the projected image should ideally be a rectangle. This is currently ensured by adjusting either the keystone correction values or the position of the IllumiShare head. It could be automated by adding a depth camera, computing the surface geometry based on its depth data, and then automatically adjusting the projected image. Finally, the camera and the projector need to be calibrated. Currently, the user does this by clicking on four corners of the projected image captured by the camera (before visual echo removal is enabled), although eventually image processing can be used to automate this step, as well. Fortunately, all of these setup steps must be performed only when IllumiShare is pointed at a new location. More importantly, most of the procedure could be automated.

## REMOTE INTERACTIONS INVOLVING CHILDREN

We evaluated the benefits of IllumiShare during children's remote play. Before we describe the study and give its results, in this section we first present relevant prior studies. The benefits of person, task, and reference spaces on distributed collaboration have been studied both at home and at work. We focus on the studies that involved children.

Several projects have focused on remote parent-child interactions. A study by Ames et al. [1] compared phone calls to a two-way videoconference, which is a person space sharing system. They found that having the person space made it easier for children to communicate with their parents. Another study by Yarosh et al. [12] compared parent-child interactions over a shared person space (vanilla two-way videoconference) to richer interactions with both person and task-reference spaces (two-way videoconference with a shared table system). They found that the condition with a task-reference space was preferred.

Other work has focused on child-child interactions. Yarosh et al. [14] studied the narrative and pretend play over three different instances of a person space sharing system: phone-to-phone, phone-to-laptop, and laptop-to-laptop. They found that the laptop-to-laptop condition was preferred and also most supportive of narrative and pretend play.

The study that is the most related to ours was done by Yarosh et al. [13]. They compared four different video mediated communication technologies for remote play. They had a *vanilla* person space (videoconference) condition. They also included two person space conditions with a limited task space, *local control of view* and *remote control of view*. In the local control condition, a child could use a PTZ camera to focus on an area in the remote play space. In the remote control condition, a child could focus the view of the remote child on an area of the local play space using a mobile device. However, task spaces in these conditions were not shared. Moreover, there was no reference space. Their final condition included both a person space and a shared task-reference space. The task-reference space was provided on an area of the floor. They found that the level of social play was higher in the person space only condition than in the other conditions. They also found that the person space only condition was the easiest. These results are inconsistent with earlier work [12], which found that in parent-child interactions, having both person and task-reference spaces is preferred. However, there was a technological limitation to the task-reference sharing system that may have impacted the findings. In particular, the task-reference space was grayscale and its resolution was low. To paraphrase one of their participants, it looked like TVs from a long time ago. This limitation may have detracted from the kids' ability to effectively interweave actions on the floor. The goal of our work was to reevaluate person and task-reference spaces during remote play when technology does not interfere with activity.

## USER STUDY

We performed a user study to evaluate IllumiShare. As an initial exploration of the device, we focused on the physical object sharing. The goals of our study were threefold. First, we wanted to explore whether IllumiShare is able to share surfaces (task-reference space) naturally and seamlessly. Second, we wanted to analyze the benefits it offers over video (person space) and if it reduces the necessity for video. Third, we wanted to see what tasks it enables.

### Communication Conditions

To compare the benefits and relative importance of sharing task-reference and person spaces, we compared video conferencing with IllumiShare condition, which we refer to as the *Video+IllumiShare* condition, to vanilla video conferencing and IllumiShare with audio conferencing conditions, which we refer to as *Video* and *IllumiShare* conditions, respectively. These conditions allowed us to compare sharing person and task-reference spaces, only the person space, and only the task-reference space.

In all three conditions, a Skype Audio connection provided the audio channel. We used ClearOne speakers with acoustic echo cancellation capabilities as both speakers and microphones. In Video and Video+IllumiShare conditions, a Skype Video connection and standard webcams provided the video channel. In the IllumiShare and Video+IllumiShare conditions, IllumiShare provided the shared surface channel.

### Participants

We recruited eight pairs of children between the ages of 9 and 11 (mean 10.0). Four of the pairs were boys and four were girls. One pair of boys was twins and the remaining pairs were friends. The children were all comfortable with gaming devices and video chatting with others. All of them reported playing video games at least a few times a month, and a majority reported playing them at least a few times a week. All of them also reported playing video games together with a friend in the same room, but less than half reported playing with friends remotely. Finally, most of the children reported video chatting at least once, while some reported that they do so at least a few times a month.

### Setting

The study sessions took place in two adjacent rooms connected to a common observer room. The experimental setup is shown in Figure 7. An IllumiShare was set up on a table in each room with the head about 80cm above the table surface, which created a shared area approximately 9x12” in size. A 12” screen displayed a full screen video of the remote participant. A ClearOne speaker was placed next to the screen to provide the audio link between the rooms.

Each room had a box of age appropriate toys for both boys and girls (e.g., action figures, Hello Kitty dolls, magazines, comic books, dice games, card games, stickers, etc.). The toys in the two boxes were identical except for the magazines and comics. Each room also had stationery children could play with (e.g., paper, pen, markers, scissors, colored sticky notes, a dry erase board with markers, etc.). The children were also invited to bring along a game they like to play at home. A few children brought toys, such as board games, cars, and action figures.

### Procedure

When the children arrived, we took them into one of the study rooms where they first filled out a questionnaire on their experience with video games and video chat. The children then played face-to-face for five minutes, during which time they were free to explore the games in their toy boxes. Then we explained the setup to both participants, following which one of the participants, along with a box of toys, was taken to the other study room. The children then played in four consecutive ten minute sessions for a total of forty minutes of play time. The children experienced the Video+IllumiShare condition in two of the sessions, Video in one session, and IllumiShare in the remaining session. The order of the conditions was counterbalanced with gender; however, the two Video+IllumiShare conditions were never adjacent to each other (see Table 1). The reason for having the Video+IllumiShare condition twice was because we were interested in the impact on remote play of removing and adding IllumiShare or Video. At the end of the four sessions, the participants completed a post task questionnaire about their experiences with each of the communication conditions.

### Data Collection

In addition to collecting the participants’ answers to the pre and post playtime questionnaires, we also recorded videos of each participant from multiple views. One view focused on the shared surface, while the other two took in the overall scene from different angles.

We used to recordings to extract participant quotes and empirically analyze the sessions. We analyzed two aspects of the recordings. First, we analyzed the tasks the children performed, including their start and end times. Second, we analyzed changes in play and engagement level following a transition from one condition to another. We specifically noted whether a transition (a) decreased the engagement level or stopped a task, which we called a *limiting transition*, or (b) increased the engagement level or spurred a new task, which we called an *empowering transition*.

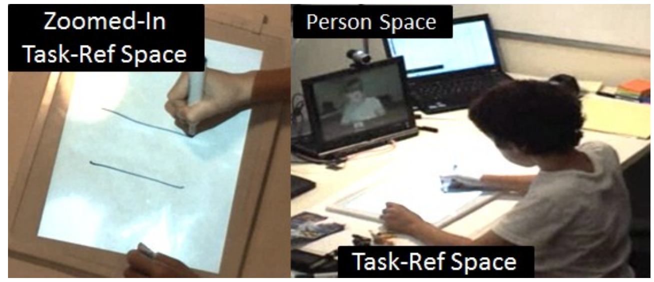


**Figure 7. Experimental study setup.**

**Table 1. Order of conditions during play: V = Video; I = IllumiShare; VI = Video+IllumiShare.**

| # Girl Pairs | # Boy Pairs | 1st | 2nd | 3rd | 4th |
|---|---|---|---|---|---|
| 1 | 1 | VI | V | VI | I |
| 1 | 1 | V | VI | I | VI |
| 1 | 1 | VI | I | VI | V |
| 1 | 1 | I | VI | V | VI |

## USER STUDY RESULTS

In this section, we present our observations of children playing in the different experimental conditions, questionnaire results, and empirical data we extracted from the video recordings of the participants.

### Play Observations

Generally, the kids did not have problems playing during the study. They immediately understood the IllumiShare semantics. They mentally mapped anything that was lit up by the projector as public and everything else as private. All of them understood that if they pointed to a place in the lit up area, the other could see where they were pointing.

They were also able to overcome some interaction restrictions. For example, with IllumiShare, a user cannot move remote physical objects. This was usually not an issue for our participants as they simply asked each other to clear the area or move objects on it. Also, if a game could not be played remotely with its original rules, they modified the rules. For example, in the card game War, both children put down cards and the winner is supposed to take them. However, the winner cannot take away the remote card. To solve this problem, they created two winner piles, one for the cards won by the local user and one for the cards won by the remote user, as well as, new rules for how to use the piles later in the game. They also figured out ways to avoid conflicting with each other. For example, they sometimes divided the shared space into two areas in which they could play in parallel. On the other hand, we also observed playful planned conflicts, such as toy piles, drawing different parts of the same object at the same time, and tracing each other’s drawings. Thus, IllumiShare was easy to understand and encouraged them to interact naturally.

*Video+IllumiShare condition*: The children seemed to thrive in the Video+IllumiShare condition. All pairs were fully engaged as soon as the condition started. Often, the first reaction to having both IllumiShare and Video was to

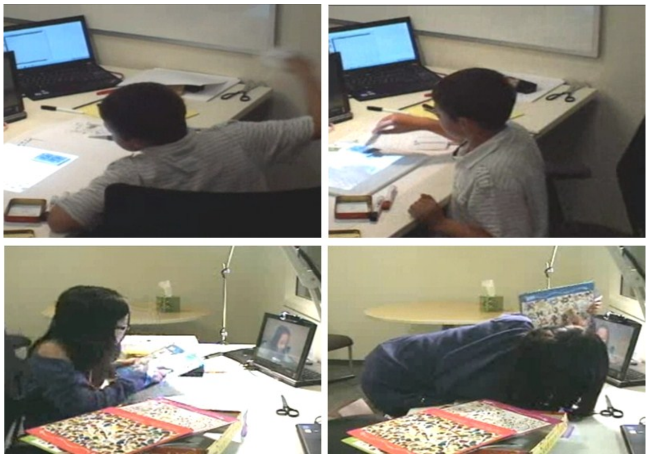

**Figure 8. (top-left) Animated body gestures with Video+IllumiShare; (top-right) subdued gestures with no Video; (bottom-left) pointing with Video+IllumiShare; (bottom-right) pointing without IllumiShare.**

write a quick note in the shared area, and then demand the attention of the other person by calling out to them and looking at their video. When they played with toys, they often showed them to each other using both IllumiShare and Video. They also interacted via the toys, such as fighting with action figures (Figure 1 left) and arranging toys in playful ways. In addition, they seemed to be animated about what they were doing even if the task was taking place on the shared surface. For instance, when a pair of boys was playing the card game War, one of them used whole body gestures as he put cards down and said "*I summon…an ace!*" in an authoritative wizard-like voice as he slammed his card down on the table (Figure 8 top-left). Meanwhile, when a group of girls played I Spy, each of them had a copy of the board and when one found an item, she would get extremely excited, put the board into the shared area and point at the item's location. The other would immediately look at the remote board and where the friend's hand was pointing in order to find that same location on her own board (Figure 8 bottom-left).

*IllumiShare condition*: When they had IllumiShare but not Video, they sometimes polled to see if the other person was there. For instance, if one of them was doing something off camera, the other could not tell if they were still there. In addition, although they performed mostly the same tasks in the IllumiShare and Video+IllumiShare conditions, they tended to be less visually animated without the video. For instance, the same pair of boys whose game of War we described earlier also played War without the video. In this case, body actions, such as hand motions, were subdued and took place on the shared surface (Figure 8 top-right).

*Video condition*: When they had only Video, they seemed to struggle more to play compared to the other conditions. Some pairs adapted quickly. For instance, the pair of girls who played I Spy with Video+IllumiShare also played it with Video. However, to point at a location, they had to bring the I Spy board up to the camera. To be sure that that they were pointing at the right place, they put the board on an angle and squeezed their heads between the board and the camera (Figure 8 bottom-right). Other pairs tried new things. For example, a pair of boys decided to virtually slap each other and throw things at one another by pretending to slap or throw things at the webcam. In some cases, the video condition resulted in awkward silence periods during which the children would glance around the room and look at each other without talking. In one such instance, the silence was broken with "*Oh look, scissors. I can't wait until the table thing works*". Note that the children usually referred to IllumiShare as "table."

We also analyzed the tasks that the children engaged in. Overall, we coded 40 different tasks, which we divided into five categories: 1) 20 tasks were pen and paper based (e.g., drawing, writing); 2) 8 were card or dice games (e.g., War, Bowling Dice); 3) 4 involved only showing things (e.g., show magazine); 4) 3 were gesture games (e.g., rock paper scissors; dancing); 1) and 4 were other games (e.g., I Spy, mancala). The one remaining task was brainstorming about what to do next, which happened throughout.

In addition, we analyzed the types of tasks that were performed in each condition. Pen and paper, dice, and card tasks were predominantly performed when IllumiShare was available. On the other hand, participants played more gesture games when Video was available. Other games and showing things to each other were performed mostly when both IllumiShare and Video were available.

### Preference, Fun, and Ease of Play

Answers from the questionnaire are shown in Figure 9. Most of the children (14/16) selected Video+IllumiShare as the easiest and most fun condition. They explained that it was "*just like being next to them*" and that "*best was when we talked together and (made) movies on the table*". As Figure 9 also shows, the children were split on whether the Video or the IllumiShare condition was the hardest. Some said that "*just table is hard because you couldn't see each other*" while others said that "*just video is hard because you can't play a game*". On the other hand, they tended to rank the Video condition less fun than the IllumiShare condition (11/16). They stated that "*just video was more of a talk thing. If you wanted to just talk, you would be fine. But if you wanted to play, then video wasn't good*" and "*it was kind of hard to play I Spy without the table*". Others had more general comments like "*instead of holding it up to the camera, you could just put it on the screen*".

The children were also asked to rank each of the conditions on a 7-point scale in terms of how much they liked each condition (Dislike=1, Like=7) and how easy the condition was (Hard=1, Easy=7). As Figure 10 shows, the children liked the Video+IllumiShare condition (6.5/7) more than the Video (4.25/7) and the IllumiShare (4.18/7) conditions. A Related Samples Friedman's Two-Way ANOVA revealed a main condition effect ($\chi^2(2)=16.222$) and post-hoc pair-wise comparisons using Wilcoxon Signed Ranked Test showed that the Video+IllumiShare condition was rated significantly higher the Video (Z=-3.298,p=.001) and IllumiShare (Z=-3.145,p=.002) conditions.

Figure 10 also shows that the Video+IllumiShare condition (6.25/7) was rated easier to play than the Video (3.93/7) and IllumiShare (4.00/7) conditions. A Related Samples Friedman's Two-Way ANOVA revealed a main condition effect ($\chi^2(2)=19.311$) and post-hoc pair-wise comparisons using Wilcoxon Signed Ranked Test showed that the Video+IllumiShare condition was rated significantly more fun than the Video (Z=-3.051,p=.002) and IllumiShare (Z=-3.393,p=.001) conditions.

The final set of questions in the questionnaire asked the participants to select which of the conditions they would like to (a) have at home and (b) use to do homework. As Figure 11 shows, most of the participants preferred Video+IllumiShare for home (15/16) and homework (14/16). They liked having both at home because "*you can see each other and play on the table*", "*because with it I could see the person's face and hands*", "*I would like to have table and video because you can see the person and see what they are doing*", and "*I would like to have this at home because you can do whatever you (want)*". They liked having both for homework because "*if there is like blocks to count, you can see how many there are*", "*I could see the other person draw out the problem*", "*table and video because they don't only tell you, but they can show you examples*", and "*you would be able to write stuff with them easiest*". The single participant who did not choose Video+IllumiShare for home chose Video instead. Of the two participants who did not choose it for homework, each chose one of the other conditions. The girl who chose IllumiShare for homework said that she choose it because "*I could see the other person draw out the problem*", which acknowledges a desire for more task-reference space than person space while doing homework.

Overall, questionnaire results show that the best condition was Video+IllumiShare. Moreover, while IllumiShare and Video conditions were often ranked similarly, more than twice as many participants (11 vs. 5) ranked Video as being less fun than IllumiShare.

### Disruptions to Engagement Levels

We also evaluated the impact inclusion or exclusion of person space (Video) and task-reference space (IllumiShare) had on the children's level of engagement. Without IllumiShare, the children struggled to find something to do. One girl asked her friend "*What can we do over video chat*" as she rummaged through the toy box (Figure 12 left) to which her friend responded "*I don't know*". A pair of boys wondered "*What can we do?*" and concluded "*Just talk, I guess*". They seemed to anticipate that the removal of IllumiShare will make things difficult. When we told them it was being turned off, their reactions ranged from a confused "*Ok…*" to "*This is bad! This is very, very bad!*" When we added it back, the reactions ranged from "*Oh good*" to "*Yaaaaaay, Table!*" (Figure 12 right). On the other hand, both the removal and addition of person task had little impact on level of engagement. When we told them the video was being taken away, they were mostly concerned about not being able to talk. When we

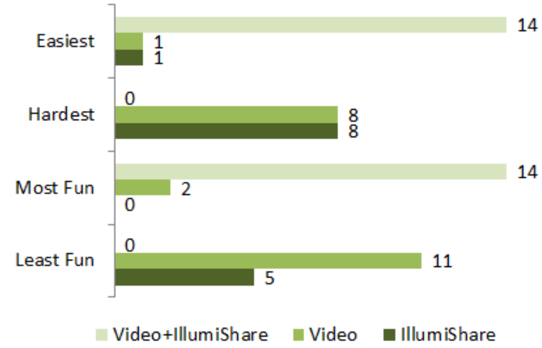


**Figure 9. The number of participants who selected each condition as easiest/hardest to use and most/least fun to play.**

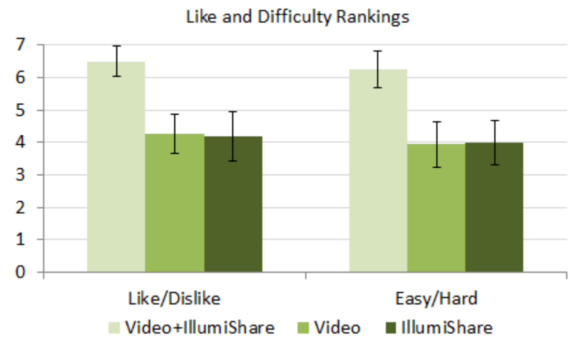


**Figure 10. Average rankings of the conditions on scales of Dislike=1 to Like=7 and Hard=1 to Easy=7 (95% confidence interval shown).**

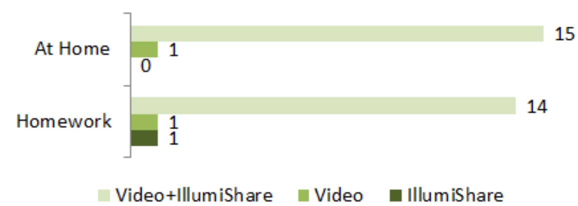


**Figure 11. The number of participants who selected each condition as the one they wanted for home and homework.**

**Figure 12. (left) Figuring out what to without IllumiShare and (right) celebrating when IllumiShare is added.**

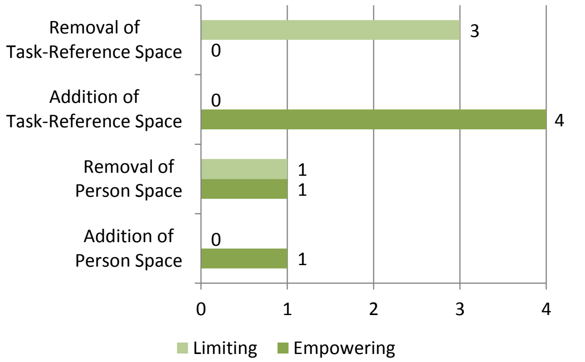


**Figure 13. The number of empowering and limiting transitions between conditions.**

told them they could still talk, a girl said to her friend "*Oh, we can still talk and we still have the table. Sweet!*", while a boy said to his friend "*We can still hear each other, dude*".

### Disruptions to Play Tasks

We were also interested in the how disruptive or empowering adding or removing the person (Video) and task-reference space (IllumiShare) was to the play task. Specifically, we wanted to know if removing one of these spaces is a limiting disruption, and alternatively, if adding one of these spaces is an empowering disruption.

We counted the number transitions between the conditions that were limiting or empowering. Figure 13 shows the totals. The top two sets of totals in Figure 13 show the impact of removing or adding task-reference space to the interaction. Removing the task-reference space caused three limiting and no empowering disruptions. In one case, a girl was about to show a magazine to her friend, but when we told her that IllumiShare is being turned off, she put the magazine away and tried to figure out something else to do. When asked about this in the debrief, she said "*it's hard to hold it up*" to the camera. Another group was about to start playing a Wack-a-Mole card game. When they were told that the table was being turned off, one of them said "*We can do something else, just put the cards away*". In a third group, a boy was asking his friend to put a magazine on the shared surface so that he could trace it, but then stopped asking for that once he heard that IllumiShare was being turned off. On the other hand, adding the task-reference space back into the interaction resulted in four empowering and no limiting disruptions. One set of participants went from reading to each other to playing with toys, while another set went from drawing in parallel to one drawing a world for the other to use as a playground for her toy.

The bottom two sets of totals in Figure 13 show the impact of removing and adding the person space. Removing it was limiting once and empowering once, while adding it was empowering once. As one of the boys said when we added video back, "*Ok, let's do something else now that we can do more now*". Overall, there is no clear type of disruption caused by the removal or addition of the person space.

## DISCUSSION

In this section, we first compare our results to those of prior work. Next, we discuss some actions and comments from our participants that can help us improve IllumiShare. Then we discuss IllumiShare in a broader context.

### Comparison to Prior Results

As mentioned earlier, Yarosh et al. [13] found that a person-only shared space system was more effective than a person and task-reference space shared system for remote child-child interactions. They acknowledged, however, that their surface sharing system had some limitations. Our work shows that it is important to address these limitations and truly achieve natural and seamless task-references space sharing before evaluating surface sharing systems. In particular, rough edges in such systems can result in an evaluation and user performance that does not generalize.

### IllumiShare Improvements

Several children said that IllumiShare would be even better if the area it shared were larger. On average, they gestured that the area should be about twice as large as it is now, which means about 18x24". A related request was zoom functionality. Specifically, they wanted to be able to zoom in on areas of magazines and comics with fine print so that the other person could read them.

Several of the pairs experienced framing issues with Video. One pair of girls decided to create towers out of boxes in front of the webcams on top of which they would play with toys (Figure 1 center). This was a frustrating experience with constant "*can you see it now?*" questions. After one girl said "*no*" several times in a row, the other girl said "*Dang it!*" It would be useful to explicitly show the camera frame to the children, perhaps as in Yarosh et al. [14].

IllumiShare does not track objects so objects from different sites can become misaligned. This did not seem to be a problem for our participants as they immediately and collaboratively realigned them. Moreover, one of the boys on purpose moved his tic-tac-toe sheet so that his O's would move on the remote sheet as a playful cheat. Nevertheless, it would be useful to give users the option to preserve alignment through object registration and tracking.

Lastly, with IllumiShare, a user cannot manipulate remote physical objects. Although, as we mentioned above, this was generally not a deterrent to play, it did prevent some tasks that require manipulating remote objects from being attempted. For instance, board games were avoided as they often require moving pieces belonging to the other user. One solution is to capture and digitize physical objects so that their digital versions can be manipulated by all users.

### Beyond Remote Play

Although we studied IllumiShare in the context of remote play, the system is useful in other collaborative scenarios.

Beyond children scenarios involving play, it can also be used in child-adult pairs. For example, the system enables remote tutors to help children with math and science homework using real pen and paper instead of digital ink or text, which can be awkward for things such as quick scribbles and equations. At work, co-workers can use IllumiShare to share a diagram or a whiteboard. For example, a remote meeting attendee can use IllumiShare to write and point at a whiteboard in a conference room. In addition, two co-workers can discuss digital presentation slides by pointing at them and marking them up together.

Moreover, IllumiShare is useful even if only one of the collaborators has it. Specifically, the non-IllumiShare user gets the rich referential awareness of the IllumiShare user. To the IllumiShare user, there is the added benefit of naturally marking up shared digital items using pen and paper, as well as, the ability to gesture and point at things.

## CONCLUSION

This paper presents two main contributions. First, it presents a new cost-effective, light-weight device called IllumiShare that provides task-reference space sharing better than existing devices. Specifically, it is the only device that shares arbitrary physical and digital objects on arbitrary surfaces. Our study of children during remote play indicates that people (a) understand IllumiShare's task-reference space sharing metaphor and (b) interact with each other naturally and seamlessly across distance using their hands and other real objects such as pen and paper, toys, cards, and dice. Second, the study also increased our understanding of the importance of person and task-reference spaces during remote play. We found that children prefer having both IllumiShare for task-reference space sharing and Skype Video for person space sharing compared to having only one of them. Moreover, we found that task-reference space removal and addition has stronger negative and positive impacts on play, respectively, than person space removal and addition.

In the future, we plan to continue to study and improve IllumiShare. It would be useful to compare it to other surface sharing systems, such as shared electronic whiteboards, to evaluate whether its complexity is worth the benefits. In addition, it would be interesting to compare card and board games through IllumiShare to digital multi-player version of these games. It would also be useful to perform longitudinal studies of remote play, and we are working on deploying IllumiShare units at homes with children. Moreover, we plan to perform a deep-dive lab evaluation using a smaller number of children pairs. We are also interested in studying the benefits of IllumiShare in enterprise settings, such as enabling remote meeting participants to interact with a whiteboard in a conference room. In terms of improving the device, we plan to increase the size of the area it shares, as well as, add zoom functionality and object tracking. We also plan to automate the steps required to setup IllumiShare.

## ACKNOWLEDGEMENTS

We thank several people from our lab for their help and advice: John Tang, Andy Wilson, Bruce Clearly, Rajesh Hegde, Zicheng Liu, Cha Zhang, Zhengyou Zhang, and Hrvoje Benko.

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