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Mirror, Mirror, On The Wall: Collaborative Screen-Mirroring for Small Groups

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ABSTRACT
Screen mirroring has been available to consumers for some time, however if every mobile device in the room supports screen mirroring to the main display (e.g. a shared TV), this necessitates a mechanism for managing its use. As such, this paper investigates allowing users in small intimacy groups (friends, family etc.) to self-manage mirrored use of the display, through passing/taking/requesting the display from whomever is currently mirroring to it. We examine the collaborative benefits this scheme could provide for the home, compared to existing multi-device use and existing screen mirroring implementations. Results indicate shared screen mirroring improves perceived collaboration, decreases dominance, preserves independence and has a positive effect on a group's activity awareness.

Author Keywords
Screen mirroring; multi-user; single display;

ACM Classification Keywords
H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

INTRODUCTION
Consumer screen mirroring technology has grown in popularity in recent years, with either Apple's Airplay[1] or Miracast[2] available in most new mobile devices, allowing the mirroring of screen content, as well as driving entirely separate presentations. Additionally, devices capable of displaying this mirrored content are ubiquitous (be it TVs, HDMI dongles such as Chromecast or software servers such as Reflector[3]), whilst projects such as Android Transporter[4] have demonstrated the capability for real-time device-to-device mirroring.

Given that, in the near future, every device in a living space might well support the sharing of device content through mirroring, the issue of who gets to mirror their content, and when, will become more pressing. For example, groups of friends and family sharing a display may be unable to adequately self-organise their usage of this mirroring functionality across their personal devices.

In this paper, we study a range of mirroring strategies that groups can use to share and self-mediate use of a receiving display across multiple screen mirroring devices, examining both potential sharing behaviours, and the effect sharing the display has on intra-group collaboration, and activity/artefact awareness.

RELATED WORK
Screen mirroring (also screen {sharing, casting, annexing}) is not a new concept, having first been demonstrated by Doug Englebart in 1968 [4] as a tool for remote collaboration. This concept has been elaborated upon in recent years: Greenberg *et al.* [16] utilized distributed screen-sharing to facilitate artifact awareness (awareness of documents and tools others are using) in groups, whilst XICE [3] proposed a toolkit for display annexation.

Commercial applications of screen mirroring have seen increasing popularity in recent years, however their adoption has not been universal, despite the ubiquity of mobile devices supporting the feature. A recent NPD survey [12] of smartphone users found a 40% awareness of the existence of screen-mirroring capabilities, with only 7% having ever used such features. Of these individuals, 75% had used this capability for mirroring videos, whilst approximately 50% had mirrored photos. Indeed the study stated that:

> "Bringing sharing experiences to a larger consumer base will require simplifying hardware requirements [and] amplifying the value of being able to share content across screens"

Collaborative Browsing In The Home
A notable absence from discussion in the NPD second-screening report was that of collaborative browsing, an activity known to occur frequently in the home. In 2009 Morris *et al.* [2] found that, of the co-located searches that occurred in the home, 58% were informational searches, with the majority of searches being spontaneous (70.6%) and lasting only a few minutes (64.7%), occurring in pairs (70.6%) or groups of three or four family members or friends (29.4%). Most searches were conducted using a single, shared machine (laptop/desktop) (76.5%).

A 2013 update [9] to their research found that the majority of smartphone users (92.8%) used their phones to engage in co-

[1] `http://www.apple.com/airplay/`
[2] `http://www.wi-fi.org/wi-fi-certified-miracast`
[3] `http://www.airsquirrels.com/reflector/`
[4] `http://esrlabs.com/android-transporter/`

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located collaborative searches with several people simultaneously, with these events occurring on a frequent basis (38.9% doing so at least once per day, and 65.6% at least a few times per week).

There have been a number of studies looking at the facilitation of collaborative web browsing, for example Schmid *et al*. [13] recently explored multi-device collaborative search using a shared display, however this required intercepting requests using a forward proxy, raising potential privacy concerns. PlayByPlay [21] implemented collaborative web browsing across both desktop and mobile devices, using saved IM sessions as a means for managing search activity across clients, whilst CoSearch [1] enabled co-located collaborative web search using a shared PC, showing that this preserved communication and collaboration.

Single/Multi-display Groupware

In collaborative terms, screen sharing has largely been supplanted by Single-Display Groupware (SDG, supporting collaboration between users that are physically close via a shared display) and Multi-Display Groupware (MDG, supporting collaboration using multiple displays). Within SDG, work has centered around shared displays or tabletops facilitating multiple users, for example via multi-touch [10].

MDG has extended these concepts, allowing for flexible combinations of displays, for example supporting personal and shared workspaces [20], shared workspaces and public displays [11] and other such permutations of personal/private/shared workspaces [17].

Of note within this field is the effect of having personal workspaces with shared displays, versus one single shared display. SDG configurations have been shown to provide more awareness, whilst personal displays have been found to offer "sheltered" and potentially personalized workspaces with less visual distraction, with the end result of better supporting individual cognition [19].

Awareness

Awareness within collaborative systems is a key issue and has been studied for many years, with a variety of definitions [5]. For the purposes of this paper, the most relevant interpretations are those of Greenberg *et al*. [6], and Schmidt [14].

Greenberg *et al*. [6] discussed the concept of workspace awareness ("one persons understanding of another person's interaction with a shared workspace") [16], specifically artefact ("what objects are they working on") and action ("what are they doing") [6, 5] awareness. Schmidt [14] referred to awareness in terms of actors; actors both monitor activities, and display activities perceived as relevant to their colleagues. The effect of this is improved situation awareness, which in turn allows for more effective collaboration. [6]

Awareness is a necessary trait for effective collaboration; in the home, this activity awareness is typically achieved through a shared focal point (e.g. TV/laptop/tablet/phone as seen in the collaborative browsing studies mentioned previously), however there is no catch-all solution that both facilitates independence and provides activity awareness to whomever else is in the room.

Overview

Whilst technologies such as second screening and social TV have seen considerable research, the interaction between those in the room has perhaps been underinvestigated. Collaborative behaviour in the home is well understood, but systems designed to support this collaboration, in a manner that utilizes the technology typically available (mobile devices, a large shared TV) and is appropriate for the home context (relying on simple interfaces and established behaviours to provide activity awareness) have yet to be examined fully.

STUDY

Whilst there has been growth in screen-mirroring technology, specifically in consumer devices, multi-user use is often poorly facilitated, for example with users having to disconnect from the display to allow another user to mirror his or her device, a potentially laborious procedure to repeat.

To address this issue we set out to examine the merits of facilitating shared use of the receiving TV (given the possibility that every device in the room supports mirroring, and that the TV is typically the best display in the room and as such provides a shared focal point that should be opened up to social use). We chose to study this within the confines of small group collaboration, in order to provide a realistic task with which to motivate usage (e.g. a small group of friends or family sharing use of a TV in a living room). Additionally, we wanted to examine the effect screen mirroring had on artefact/activity awareness within the group, which in turn influences a groups ability to collaborate effectively.

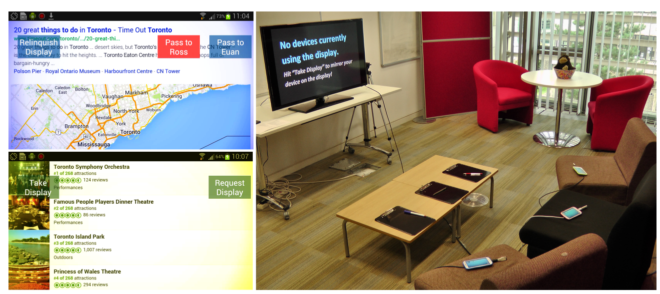

Figure 1. Left: client UI (top is current "owner" of the TV, bottom is another participant). The coloured glow around the edges was unique to each device, whilst overlayed semi-transparent buttons enabled management of the shared mirroring TV. Right: Living-room-like space used for conducting study, with 3 phones (one per participant) wired up to our mirroring system.

Control Scheme: Possession of the Display

For the purposes of this study, we treated the display as a commodity that was owned by whomever was currently mirroring to it, partially influenced by previous work on sharing behaviour [8]. As such, if a user owned the display, he/she could relinquish it, or pass it to individuals that requested its use. Similarly, if a user did not possess the display, he/she could request or take it using buttons overlayed on the screen of the client device.

This control scheme satisfied a number of concerns. Firstly, there was the issue of privacy: a user must actively participate (i.e. request or take the display) in order to end up having their content mirrored to the shared display. If they no longer wished to be mirrored, they could simply relinquish the display. Secondly, we wished to examine how users would choose to manage this resource: would they see taking the display as socially acceptable, given the task is about collaboration? Or would they prefer to use a request-pass mechanism for managing display usage, a potentially more socially acceptable.

Collaborative Task

Whilst there are a number of potential use cases for shared screen-mirroring, we decided to validate its use through the potential for aiding small group collaboration in the home, evaluated via a collaborative browsing task. This allowed us to rely on previous work regarding metrics for how well groups felt they collaborated (for example using questions from Websurface [18] and Mobisurf [15]). Additionally we chose to examine how the shared screen-mirroring display affected visual attention and awareness of others activity, whilst presenting users with a typical and realistic scenario that occurs in home environments among small groups.

Our collaborative search task was a variant of the travel search task derived from Morris *et al.* [9] in other studies previously [18, 15]. Participants were given 15 minutes to plan a trip to a given city (New York, London, Sydney) and pick tourist attractions/shows to see as a group. These cities were chosen due to their abundance of potential attractions and associated English-language materials online. Participants were free to browse using their devices however they saw fit in relation to the task. This task was ecologically valid, having been shown to be conducted in the home previously, with additional validity derived from the use of consumer mobile devices and the freedom given to participants to use these devices naturally.

Participants

Six groups of three participants took part (male=13, female=5, age MEDIAN=22.2, SD=2.81), recruited in groups, on the basis that group members knew each other (being friends/family/colleagues). Additionally, participants were required to be regular users of mobile web browsers.

Experimental Design

Three conditions were examined: 1. mobile devices with no screen-mirroring (as a control; this is analogous to the situation where people use phones to collaborate over an activity); 2. mobile devices with one device permanently mirrored (representative of existing consumer screen-mirroring where unpairing/pairing devices is a costly process); and 3. mobile devices with shared screen-mirroring (use of the TV screen could be passed/taken/relinquished/requested). A split-screen approach was also considered, however ruled out on the grounds of scalability (splitting the screen does not scale well with multiple users).

The study was carried out within subjects; conditions were counterbalanced, with task cities assigned such that each condition had each city twice across the course of the study. For the permanent mirror condition, the groups were asked to volunteer a member to control the mirrored device.

Participants were seated in a sociopetal arrangement around a table, approximately 2 meters from the shared display, and approximately 30cm from each other (see Figure 1). This proximity was chosen both because of its realism (individuals sitting close together on a couch in a living room) and so that participants would have the opportunity to share what was on the screens of their devices directly by showing them to each other, in order to fully examine whether participants would use the shared display, or instead prefer physically sharing device views.

This study was designed to feature a high degree of internal and ecological validity (e.g. utilizing ecologically valid devices, in social groups representative of those found in the home, conducting a task previously found to be conducted in the home).

Implementation

Participants used Android smartphones to control the system and share content, one per participant. These devices were mirrored onto a 46inch HDTV. Mirroring was accomplished via Mobile HD-Link (MHL) cables and an HDMI switch controlled via serial port, with each device attached via an MHL cable to the switch. This was chosen over wireless display technology so as to avoid any issues with bandwidth constraints/contention, transmission issues, or performance. The cables were 3m long and not rigid, thus participants had a good degree of movement/flexibility.

Control of who currently owned the display was managed using controls overlayed on all applications within Android (see Figure 1). These controls could be moved via a long-press if they were preventing access to a particular UI element, however they could not be hidden, so as to ensure participants would not forget about the functionality. Button presses were relayed to a server controlling the HDMI switch, which in turn changed which device was currently being displayed. The switching delay was approximately 2.2 seconds, during which a black screen was shown. Additionally, when the display was relinquished entirely (i.e. no client owned the display) a screen was shown indicating that clients could mirror to the display by hitting the ”take display” button.

HYPOTHESES AND METRICS

We hypothesized that the shared display would have an effect on visual attention (attending significantly to the shared display), activity awareness (the extent to which participants were aware of each other’s activity), and perceived collaboration within the group, with participants using the shared display and it’s capability to be passed and taken to share views instead of co-viewing using the mobile devices.

In order to test these hypothesis, we recorded and analysed video footage of each participant, coding timestamps regarding which display the participant was looking at, if any. These timestamps were then parsed to form a viewing array which categorised which display each participant was looking at in

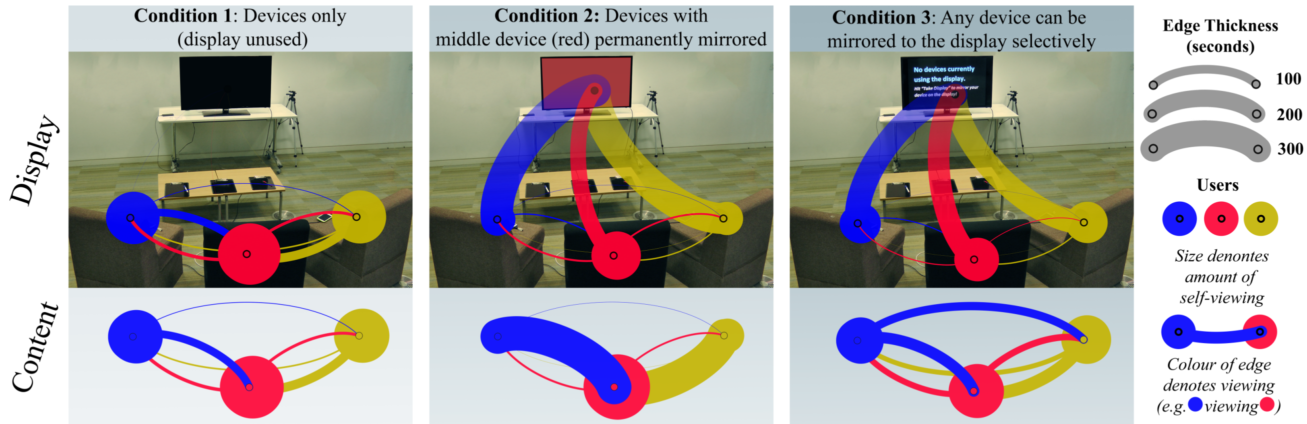

Figure 2. Mean cumulative viewing of displays (top) and user content (bottom). Each colour denotes a participant, with edge weight representing the cumulative amount of time spent looking at the node they are directed to. Top shows cumulative viewing time of the displays present (TV, and three mobile devices, one per participant), whilst bottom shows cumulative viewing of user content (presented either on the display, or on the owners device).

100ms intervals, from which mean viewing and Gini coefficients (as a measure of equity of the viewing distribution[20]; 1 denotes maximum inequality, 0 maximum equality) were calculated.

Viewing logs were generated manually by watching each participant in real time (11 hours footage in total), pressing assigned keys which coded the video log on the basis of which physical display users were attending to. These logs were then combined with logs regarding what content was mirrored, and parsed to extract cumulative viewing and co-viewing data. Footage was captured by a HD video camera placed at seated head height of participants, next to the display such that we could identify whether participants were looking at the display, their devices, or the devices of others in their group. Participants were seated and lit such that these shifts in viewing could be easily discerned by the experimenter *post hoc*.

Additionally, post-condition questionnaires were delivered including NASA TLX [7], and applicable questions derived from previous collaborative browsing studies [18, 15, 10] (7-point Likert-type) asking users about awareness and how effectively they felt they collaborated.

RESULTS

Unless otherwise stated, a repeated measures ANOVA (conducted using linear mixed-effects model fit by maximum likelihood (*lme()* in R)) was performed with a *post hoc* pairwise Tukey's test for each question/data set. p values less than 0.05 are statistically significant.

Cumulative Viewing

Figure 2 shows the cumulative viewing of both the available displays (4 in total, the 3 phones and the TV), and user activity (denoted by seating position), whilst Table 1 shows the mean cumulative viewing of a participants activity, broken down by seat and condition, excluding self-viewing (e.g. the left participant looking at the left phone display) in order to show the amount that the content on a display was shared with others.

Condition 1 can be seen as being somewhat insular: the outermost participants exhibit limited viewing of the central users activity, and little viewing of each others activity, whilst the central user has a limited awareness of the outer user's activity.

	Mean (SD) Cumulative Viewing (in seconds)		
Participant (by seat)	Condition 1	Condition 2	Condition 3
Left	45.9 (31.9)	25.5 (22.8)	194.2 (135.4)
Middle	221.2 (224.4)	884.0 (534.4)	314.8 (174.7)
Right	65.7 (71.7)	27.6 (43.3)	141.6 (55.0)

Table 1. Mean (SD) cumulative content viewed by others (excluding self-viewing) in seconds across groups, by participant position (e.g. in condition 1, the activity of the participant sitting left was viewed for an average of 45.9 seconds total by the other participants).

With the introduction of the shared display in Conditions 2 and 3, the viewing patterns change significantly, with the shared display offering a focal point for the group. Condition 2 shows a notable disparity in terms of equity of activity viewing; the mirrored user's content dominates the viewing of the group. Condition 3 exhibits greater equity in that respect, with users viewing each others content more than in any previous condition.

Gini Coefficient of $3 * 3$ cumulative viewing matrix by group, excluding self-viewing (diagonal) RM-Anova: $\chi^2(2) = 16.3, p < 0.01$				
Condition	Mean Gini Coefficient (SD)	1	2	3
1	0.432 (0.153)	–	$p < 0.05$	$p = 0.11$
2	0.611 (0.115)	–	–	$p < 0.01$
3	0.298 (0.0605)	–	–	–

Table 2. Mean Gini coefficients across conditions, calculated from each $3 * 3$ $Left, Center, Right * viewedLeft, Center, Right$ matrix of cumulative viewing, with results of *post hoc* pairwise Tukey's test.

This is confirmed in Table 2, where the equity of distribution of viewing is significantly different between Condition 2 and Conditions 1 and 3 (however not between conditions 1 and 3, predominantly because the Gini coefficient does not take into account the magnitude of viewing).

Cumulative Co-viewing

Two and three person co-viewing denotes any instant of time where two or three users were looking at the same

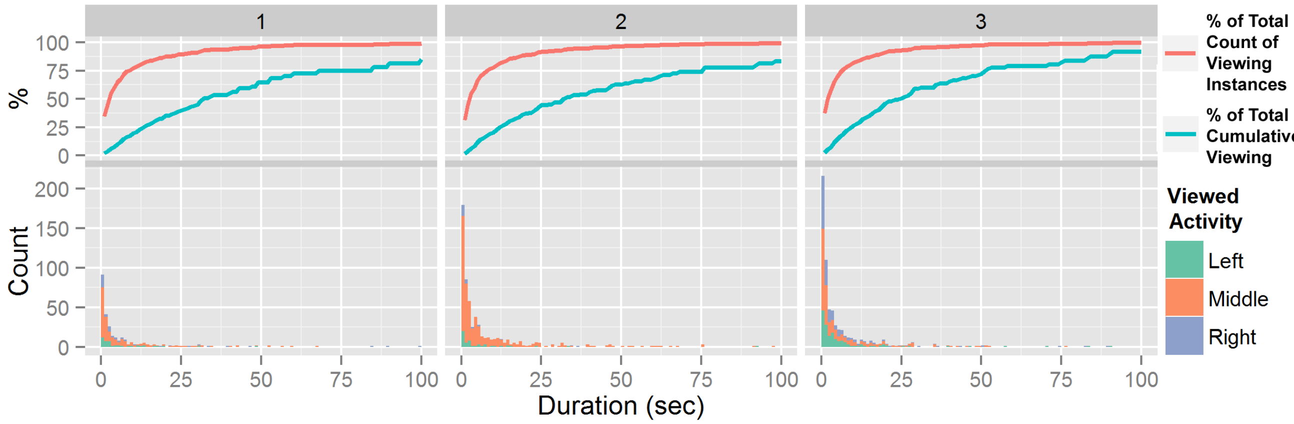

Figure 3. Graph of individual viewing behaviour across all participants (excluding self-viewing). Bottom: Histogram presents 1 second sized bins counting number of instances of viewing of a given duration. Top: Graph presenting percentage of overall cumulative viewing and percentage of overall number of viewing instances.

content/activity (with the subset of two person co-viewing within three person co-viewing excluded from two person co-viewing statistics).

Two Person Co-viewing			
	Mean (SD) Cumulative Viewing (in seconds)		
Participant (by seat)	Condition 1	Condition 2	Condition 3
Left	28.6 (23.8)	18.8 (18.5)	81.3 (74.3)
Middle	109.4 (83.1)	227.8 (68.1)	113.4 (24.3)
Right	22.6 (21.2)	21.4 (35.5)	70.1 (17.6)
Three Person Co-viewing			
Left	5.32 (5.88)	1.17 (1.34)	53.3 (34.59)
Middle	51.87 (74.0)	312.67 (269.94)	92.78 (97.91)
Right	18.75 (27.04)	0.97 (2.37)	32.5 (19.17)

Table 3. Mean (SD) cumulative content viewed in seconds across conditions, by participant position, across both two and three person co-viewing.

Table 3 illustrates the equity of distribution of two and three person co-viewing across conditions: conditions 1 and 2 feature dominance by the middle participant in terms of activity coviewed, in contrast to condition 3 where, again, a more equitable distribution of viewing across different participant's activity is demonstrated.

Gini Coefficient of Two Person Co-viewing RM-Anova: $\chi^2(2) = 18.36, p < 0.01$				
Condition	Mean Gini Coefficient (SD)	1	2	3
1	0.367 (0.077)	–	$p < 0.05$	$p < 0.05$
2	0.55 (0.139)	–	–	$p < 0.01$
3	0.209 (0.118)	–	–	–
Gini Coefficient of Three Person Co-viewing RM-Anova: $\chi^2(2) = 10.25, p < 0.01$				
1	0.469 (0.175)	–	$p = 0.223$	$p = 0.191$
2	0.605 (0.14)	–	–	$p < 0.01$
3	0.327 (0.1)	–	–	–

Table 4. Mean Gini coefficients by two and three person co-viewing, calculated from each $3 * 1$ $viewedLeft, Center, Right$ matrix of cumulative viewing, with results of *post hoc* pairwise Tukey's test.

Table 4 confirms this view, with condition 3 exhibiting the lowest mean Gini coefficients, in contrast to condition 2 which features the highest mean Gini coefficients, an indicator of the bias toward viewing the middle participants content. Indeed the draw of viewing the shared display is such that it draws the focus of the other participants from their own devices, such that they view the central participant's activity far more than they chose to do so in condition 1.

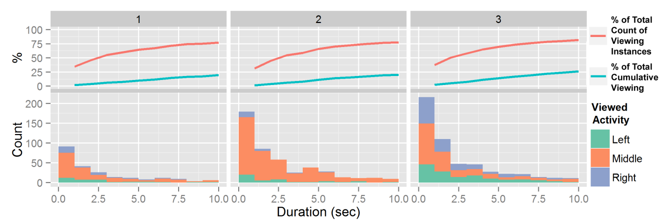

Figure 4. Graph of individual viewing behaviour across all participants (excluding self-viewing), focussing on viewing instances between 0-10 seconds. Bottom: Histogram presents 1 second sized bins counting number of instances of viewing of a given duration. Top: Graph presenting percentage of overall cumulative viewing and percentage of overall number of viewing instances.

Viewing Behaviour

We further analysed the viewing data collected by looking at time series histograms of viewing instances (using 1 second sized bins) in order to determine how participants gained awareness.

Figure 3 shows the viewing of each individual's content broken down by length of view; over all three conditions, ~75% of the total instances of viewing lasted between 0-6 seconds, however this typically only constituted ~20% of the overall viewing.

Figure 4 shows a zoomed in view of Figure 3, constrained to viewing instances lasting between 0-10 seconds. Of particular note here is the viewing distribution exhibited: Condition 1 and 2 show similar distributions, with the difference that Condition 2 is ~100% longer at each viewing interval.

Condition 3 shows a similar viewing distribution to condition 2 (with a heavy right skew toward the 0-2 second bins), however a greater proportion of the left and right participants activity is now apparent.

Question	Condition 1	Condition 2	Condition 3	Friedman Test	Wilcoxon *Post-hoc* ($p < 0.05$)
WS-1: We were able to collaborate effectively	3.94 (1.55)	4.28 (1.23)	5.17 (0.924)	$\chi^2(2) = 8.03, p < 0.05$	3-1, 3-2
WS-2: We were able to work independently to complete the task	4.89 (1.08)	3.33 (1.37)	4.78 (1.22)	$\chi^2(2) = 12.7, p < 0.01$	3-2, 2-1
WS-3: It was easy to discuss the information we found	4.06 (1.63)	4.72 (1.18)	5.39 (0.85)	$\chi^2(2) = 11.6, p < 0.01$	3-1
WS-4: We were able to work together to complete the task	4.67 (1.08)	4.72 (1.23)	5.33 (1.08)	$p = 0.053$	NA
WS-5: I was able to actively participate in completing the task	4.72 (1.27)	4.67 (1.37)	5.44 (0.984)	$\chi^2(2) = 6, p < 0.05$	None
MO-1: How well did the system support collaboration?	2.83 (1.82)	3.67 (1.71)	5 (1.08)	$\chi^2(2) = 11.5, p < 0.01$	3-1, 3-2
MO-2: How well did the system support you to share particular information with a particular user in the group?	3.11 (2.05)	3.28 (1.87)	4.83 (1.29)	$\chi^2(2) = 8.03, p < 0.05$	3-1, 3-2
MO-3: How well did the system support you to share particular information with everyone in the group?	2.17 (2.18)	3.94 (1.98)	5.17 (1.04)	$\chi^2(2) = 16, p < 0.01$	2-1, 3-1
MO-4: How well did the system support you to see/review what the other users were talking about?	2.89 (1.97)	3.39 (1.69)	5.22 (1.06)	$\chi^2(2) = 12, p < 0.01$	3-1, 3-2
WE-1: I was aware of what other users were doing	2.83 (1.54)	3.39 (1.61)	4.78 (1.31)	$\chi^2(2) = 14.7, p < 0.01$	3-1

Table 5. Questions derived from previous studies. WS: WebSurface[18], MO: Mobisurf[15], WE: WeSearch[10]. Questions were 7-point Likert scale (results range from 0-6, higher is better). Means with standard deviations are presented across conditions. A Friedman test was conducted with *post hoc* Bonferroni corrected Wilcoxon tests.

Co-viewing Behaviour

The distributions of two and three person co-viewing behaviour (see Figures 5 and 6) exhibit many of the same traits as previously discussed, for example the heavy right-skewed distribution, and the majority of the viewing instances lasting between 0-6 seconds in length.

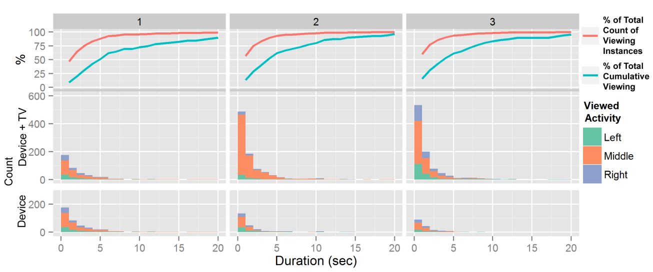

Figure 5. Graph of two person co-viewing behaviour across all participants. Middle: Histogram presents 1 second sized bins counting number of instances of viewing of a given duration, involving mixed-mode viewing (i.e. a combination of TV/device). Top: Graph presenting percentage of overall cumulative viewing and percentage of overall number of viewing instances. Bottom: Histogram of viewing excluding TV.

Of note within these Figures is the extent to which co-viewing occurred using the devices (infrequently), or using a combination of device and shared display (frequently), as an indicator of how often pairs or tuples of participants shared the common focal point of a device.

Whilst two and three person co-viewing still utilized devices as shared screens in conditions 2 and 3, the occurrence of this behaviour decreased significantly, with the majority of co-viewing involving a combination of device and shared display. This transition toward heavy use of the shared display illustrates its potential usefulness above and beyond device based sharing.

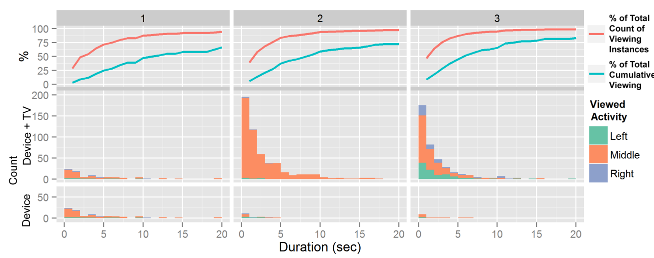

Figure 6. Graph of three person co-viewing behaviour across all participants. Middle: Histogram presents 1 second sized bins counting number of instances of viewing of a given duration, involving mixed-mode viewing (i.e. a combination of TV/device). Top: Graph presenting percentage of overall cumulative viewing and percentage of overall number of viewing instances. Bottom: Histogram of viewing excluding TV.

Indeed, three person co-viewing was barely prevalent in Condition 1, however this behaviour was clearly facilitated well by the shared display, hence the orders-of-magnitude increase in three person co-viewing when the shared display was introduced in Conditions 2 and 3.

Questionnaire

Our post-condition questionnaires (see Table 5) revealed some of the consequences of both providing a mirrored display, and facilitating shared-mirroring.

In terms of perceived collaboration, users responded positively to the shared screen mirroring, with statistically better ratings in response to WS-1 and MO-1 with respect to condition 3. Indeed WE-1 indicated why this was so, with users reporting a significant different in terms of awareness of what others were doing, indicating awareness was improved by the shared screen mirroring system.

Of note was the response to **"We were able to work independently to complete the task"** with condition 2 found to be significantly different (for the worse) than both condition 1 and 3, suggesting that the fixed screen dominance actually compromised independence within the group.

There was also a presentational aspect to the system, with the responses to MO-4 suggesting users took control of the display in order to present information to the group and aid in discussion.

Controls for Managing Mirrored Display

We additionally examined participant usage of the control scheme for our shared screen mirroring system. From table 6 we can see that taking the display from whomever currently possessed it was the prevalent means of display management, in contrast to the request-pass mechanism implemented (which required not one action (pressing the take button), but two actions across two users (pressing the request button and waiting for the receiver) in order to transfer the display).

	Request	Pass	Take	Relinquish
Total Occurrences	18	17	59	13
Mean Acceptability (SD)	4.72 (1.36)		4.83 (1.34)	NA

Table 6. Usage of display management controls provided in condition 3. Acceptability ranged from 0 (lowest) to 6 (highest) on a 7-point Likert scale. N.B. One participant was omitted as an outlier for having a request count more than two standard deviations from the mean.

Whilst participants reported feeling adequately notified when someone requested the display (MD:4.5, SD:1.38), one participant's results was omitted due to a large amount of requests made in a short period, potentially indicating issues with such mechanisms if the requester feels that the owner of the display has not been adequately notified, or has been ignored.

DISCUSSION

Our analyses show that in introducing a mirrored display that does not support flexibly changing the content or activity mirrored to it, there are a number of effects on collaboration, in terms of compromising the independence of collaborators and compromising a group's ability to be aware of each members activity.

Our proposed shared screen mirroring solution allows for the independence that users found when using only mobile devices for collaboration, whilst significantly improving group awareness of individual's activity.

Equity of Awareness and Independence

Our analysis of the cumulative group viewing suggests that the primary factor inhibiting the viewing of others content is the accessibility of that view; in the device-only condition, viewing (and co-viewing) were dominated by the central participant, whose device was most easily accessible to the other group members.

This poses a problem, in that there are a subset of group users that are essentially cut off from observing each other. The central user, whose view is most accessible, contributes disproportionately to the collaborative experience.

Given that our experimental seating arrangement was designed to be accessible and sociopetal, it could be expected that these issues would be exacerbated in a real-world living room environment, where the seating arrangements are less accessible, and potentially dispersed over a greater area. Thus the large TV display provides obvious benefits regarding being able to make whomever is in the room aware of your activity, in a way that does not disrupt their current ongoing device activity in the room.

Indeed this is where it would be expected that current screen-mirroring technology would provide an ideal means toward facilitating better awareness of activity. However, our results show that this is not the case; in utilizing a screen-mirroring solution that does not facilitate multi-user management of the shared display (Condition 2) we are limited to only one user (whomever has paired to the screen-mirroring device) having the ability to reach the group.

This compromises collaboration by undermining the independence of the other users: the shared display, and by extension the user's activity that is mirrored to that display, is viewed to the extent that said user essentially leads the collaborative task. There may be cases where this is beneficial, however in this study this was not the case. The reasons for this are that in this condition, there still exist the dual problems of there being a subset of group users that are essentially cut off from observing each other, and the central user contributing disproportionately to the collaborative experience.

We posit that these problems can be addressed by exposing a simple set of functionality for enabling flexible use of the mirroring display. Our shared screen mirroring system (Condition 3) has been shown to improve perceived collaboration, as well as providing an equity of awareness which allows every user to potentially contribute and present to the group as a whole, and allows users to retain their independence.

Self-Management of the Display: Taking is Sharing

Our system enabled a basic set of functionality for transferring and relinquishing use of the display: request-pass, take, and relinquish; of these, participants showed a strong inclination toward taking the display, both in terms of frequency of use, and self-rated acceptability.

In opening the display up to be managed by members of the group, this allowed users to work fluidly together, using their social capabilities to determine the acceptability of taking the display (in order to present their own activity or content to the group) at any given moment.

Shared Focus of Attention

Utilizing the shared display additionally provided a shared focal point for the group; incidence of two and three person co-viewing increased dramatically in the shared display conditions, providing users with a shared reference point which we believe aided in the communication and discussion necessary for effective collaboration. Indeed, this represents an additional benefit regarding utilizing the display over, for example, tablet or mobile devices for providing awareness, as the shared display typically provides a reference point accessible to anyone in the room.

Use Cases

We foresee that facilitating shared screen mirroring behaviours might have an impact on other kinds of collaboration than have been considered here. For example tasks where multiple parties must come to some kind of consensus (e.g. planning where to go to eat, what to watch in an evening etc.), or indeed any task involving flexible sharing of user activity or media content (e.g. presenting a video to the group, at which point a friend seamlessly takes the display to show a follow up video/app/website) would be likely to benefit from having the capability to use the nearest TV for flexibly mirroring content.

Limitations and Future Work

Further work will be required in order to establish external validity and user appropriation of shared mirroring TVs in the home. We anticipate that different social groups and contexts will result in markedly different behaviours and uses as users begin to explore the sharing capability these displays would enable. Additionally, we wish to explore the capability for sub-dividing the screen to allow multi-user mirroring, and the extent that this might potentially compromise use of the shared display (through the increased visual load, decreased area for representing mirrored content, and the loss of a single shared focal point).

CONCLUSIONS

Current screen mirroring technology, where a single device/user is paired with a TV, can aid collaboration in groups. However there are negative side effects, specifically with respect to group awareness being dominated by the activity of the mirrored user, leading to the compromise of independence within the group.

Our shared screen mirroring system significantly improves a small group's ability to collaborate, by enabling device users to pass/take/relinquish the display as required. Through a basic set of behaviours for managing use of the display, our shared screen mirroring system was shown to better facilitate collaboration and content sharing in small groups, resulting in greater equity of participation and awareness of others' activity. In opening the display up to the group, this allows fringe members to more actively participate, sharing content with members they were unlikely to share with previously.

We suggest that shared screen mirroring, and the controls we have presented in this paper, represent a viable extension to existing screen mirroring technologies that could be readily implemented, within the Miracast standard for example, thus enabling new sharing behaviours and interactions and lending further value to screen mirroring in the home.

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