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A taxonomy for and analysis of multi-person-display ecosystems

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Abstract Interactive displays are increasingly being distributed in a broad spectrum of everyday life environments: they have very diverse form factors and portability characteristics, support a variety of interaction techniques, and can be used by a variable number of people. The *coupling* of multiple displays creates an interactive "ecosystem of displays". Such an ecosystem is suitable for particular social contexts, which in turn generates novel settings for communication and performance and challenges in ownership. This paper aims at providing a design space that can inform the designers of such ecosystems. To this end, we provide a taxonomy that builds on the size of the ecosystem and on the degree of individual engagement as dimensions. We recognize areas where physical constraints imply certain kinds of social engagement, versus other areas where further work on interaction techniques for coupling displays can open new design spaces.

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1 Introduction

Display devices are now available in a broad and diverse spectrum of sizes, input/output capabilities, resolution, power usage and portability. When considering a single display its form factor typically defines its social affordances [46]. A handheld display is comfortably visible by one user at a time; a large wall display is visible by multiple users simultaneously and an interactive multi-touch tabletop such as the DiamondTouch [14] affords the simultaneous interaction of two to eight users with, for example, novel photo sharing applications [2]. A display device's physical constraints, such as real estate, orientation and mass, strongly affect the social context of interaction it supports and this is further constrained by the users' visual angle [22], territoriality [41], and capability to reach content and manipulate the display device.

The design issues for each individual class of display device are studied extensively in related work. New ways to couple displays means novel ecosystems of interaction can be realised. As such, more complex and dynamic *geometries of interaction* can be created, where multiple users and multiple displays are linked in the interaction.

Note that by 'ecosystem', we mean the complete system of displays, people and the space in which they are placed. As we elaborate Sect. 5, this may extend beyond the area directly occupied by the screens themselves, for example, in an airport an arrivals board a few metres across may be visible to people over a large part of the arrivals hall.

In this paper, we elaborate a taxonomy of multi-person-display ecosystems so as to provide a tool for designers to approach the design space of such dynamic geometries of interaction, where multiple displays are coupled. Our approach builds on physical and social dimensions, rather than on the underlying technological solutions. As such, we target designers of interactive spaces who might note be familiar with specific middleware or protocols solutions, to provide them with a reference tool based on human factors (e.g., visual angle) and social engagement (e.g., one–one vs. one–many situations, leading to intimacy vs. presentation types of social contexts).

We distinguish and describe the three main factors affecting such geometries of interaction:

- the size of the ecosystem defined by the coupled displays
- the nature of social interaction
- the type of interaction technique that enables the coupling of displays and transfer of interface elements across displays.

We first define the scope of our analysis: i.e., what we mean with coupled displays (Sect. 2) and the range of the spectrum that we address, i.e. a *fluid middle* in between loosely and strictly coupled displays (Sect. 3). In Sect. 4 we introduce our perspective of analysis, which builds on physical attributes of the display ecosystem and on its implications in terms of social interaction. Therefore, in Sect. 5 we describe the key attributes of our multi-person-display ecosystem taxonomy in terms of scale and the nature of the social interaction. Section 6 relates the scale of the ecosystem to the social interaction space, and highlights how ecosystems in the same or similar scale can afford different types of social interaction when different coupling techniques are used. Thus, Sect. 7 details ecosystem binding methods and how they relate to social context. Finally, in Sect. 8 we draw conclusions from our study and its relevance in design.

2 Defining coupled displays

Numerous examples of systems with impressive graphics flowing between screens can be seen in our everyday lives. However, we need to understand what it means to have coupled displays beyond the superficial surface features. In order to understand this, we review two mundane scenarios where displays are clearly not coupled.

At an airport you may use your phone to look at a web version of the same schedule. This would be linked to shared underlying data on the times of airplanes but is designed for use in separate alternative interactions. Alternatively suppose you are in the airport and use your phone to upgrade your seat and then type the booking code into a kiosk to receive your new ticket. This is linked in terms of human interaction and shared underlying information but there is at most a very weak link between the interaction states of the phone and kiosk within the system.

We need to define coupling beyond such loose coupling or coupling, which exists in ones mind only. So, at a minimum coupled displays must:

- share output and/or input components of the user interface of a *single interaction* task;
- have some *system link* between their *interaction states*—it is not sufficient for the link to be in the user's mind and not sufficient that they are linked to the same deep database.

Consider an alternative travel scenario at a railway station. Imagine placing your mobile phone on a ticket vending machine and navigating your diary to a particular event, you look up to the kiosk screen and it offers a 'buy for this day' option referring to the day you can see on the mobile phone. After purchasing the ticket your phone has a 'save this journey' option to put the train and booking information back into your diary. This is fairly low-key in terms of interactions but the two displays do behave, for the duration of the interaction, as if they were an integrated interactive system. In other words, they have been *coupled* for a single interaction, and have established and displayed a system link.

3 The scope of analysis

There is a continuum of coupled displays from the fixed, through the "fluid middle" and onto loosely coupled ones relying on minimal shared data views or basic data exchange.

There are various forms of fixed multi-display arrangements, in which displays are tightly connected but do not allow any dynamic configuration or easy re-configuration. These include (1) video-walls and gigapixel visualisation displays, (2) rigidly fixed displays such as neighboring departure and arrival screens and (3) multiple desktop monitors, which are moveable but are normally kept in fixed configurations suitable for personal use.

At the opposite end of the spectrum, loosely coupled ecosystems do not rely on multiple displays to be available but instead displays are appropriated if available and as required to communicate and display content. An example of such loose coupling, suitable for many-to-many social interaction, is a mobile phone sending images via Bluetooth to a large shared display, which then displays them automatically.

Neither extreme is the focus of this paper; instead, our scope of analysis is on the dynamic centre of the continuum of coupled displays or the "fluid middle". This fluid middle includes software support for easy personal, group and opportunistic annexing [35] of displays to form larger ecosystems. Applications in this space provide an enhanced interaction experience beyond that which any one device could afford.

In the fluid middle of the continuum then there needs to be:

- a deeper understanding of the social activities, spaces, conventions and affordances suitable for multi-person display interaction (see Sect. 4);
- an implicit or explicit way for users to express the intention that displays be coupled and eventually uncoupled (see Sect. 7.1);
- system infrastructure to enable and support the connection and coordination of the individual display devices (see Sect. 7.2)

The system infrastructure will typically involve bespoke applications and middleware, for example, a closely integrated multi-player game that needs to be especially installed on each user's mobile phone [40] or a client installed on each device to facilitate screen and control sharing as in WeSpace [24]. We envisage a future where users freely link display devices and engage in collaborative interactions across them and that this will require *open architectures and protocols* and not just one off middleware solutions. An open architecture and protocols consist of standards based APIs, well-understood data model and a common interaction language.

4 Geometry, people, dynamic display ecosystems

Multi-person display ecosystems have a physical geometry beyond the simple 2-dimensional grid of pixels of a single "display". For certain classes of application the geometry is not important while for others the geometry offers new classes of interaction. A suitable open architecture and protocols could be aware of the relative orientation of both displays and people in the ecosystem. This awareness could translate into oriented views of data, varying screen resolutions and the ability to extend a display by bringing others into alignment. So, as displays are dynamically coupled into new working geometries and people move and interact in such ecosystems, how should we describe such dynamic geometries of interaction? To address this issue we look at the spatial relation between the scales of the coupled displays and the people's focal attention. This is based on the users' visual angle, which in turn depends on the size of the individual displays, as we discuss below.

4.1 Users' visual angle

Computer monitors are often arranged to subtend an angle between 30° and 45° at the eye (e.g. laptop display approximately 35 cm width at 70 cm distance and a 24″ monitor at 30″ distance). For larger displays similar viewing angles are usually found (e.g., the Blinkenlights installation [10]): as with any display, if the angle gets close to 60° it becomes difficult to scan your eyes from side to side or up and down without moving your head. There is a minimum distance to allow the display to be seen as a whole. Of course, if the visual angle gets smaller then the amount and detail of what can be displayed diminishes. Hence, Teletext on a television displays approximately 1/5 of the number of characters across its width compared with a computer monitor. As a television is usually positioned at the opposite side of a room the characters end up subtending a similar visual angle to those on the computer monitor.

When considering the relation between the size of a single display and the visual angle one can than determine in Table 1.

We have extended Weiser's classification of inch/foot/yard displays [49] and used larger, albeit slightly archaic, imperial measurements including the perch, which is 5.5 yards (as used in [16]), and the chain, which is 22 yards. The use of these imperial measurements allows us to deal with ratios of scale less than an order of magnitude that better match the scales of social interaction we are interested in.

Thus, the comfortable viewing area tends to create a multi-person-display ecosystem whose scale approaches one scale larger than the largest device itself. So a foot size display tends to afford a yard scale ecosystem and a yard size display fits best in rooms that are perch scale (e.g. a medium meeting room).

One needs to notice, though, that depending on the coupling technique (see Sect. 7) the geometry of the ecosystem can be elastic and the visual angle can vary. To further clarify the relationship between the comfortable viewing area and the scale of the ecosystem, in the following section we move from the scale of the single display to the scale of the multi-person-display ecosystem in consideration of users' focal attention (Fig. 1).

Table 1 The scale of single displays in relation to users' visual angle and distance

Scale	Example	Display size	Distance	Angle
Inch	Phone	3 cm	40 cm	4°
Foot	Tablet/laptop	35 cm	70 cm	28°
Yard	pub TV	1 m	3 m	19°
Yard	Tabletop	1 m	1 m	53°
Perch	Town centre	5 m	10 m	28°
Chain	Blinkenlights	20 m	50 m	23°

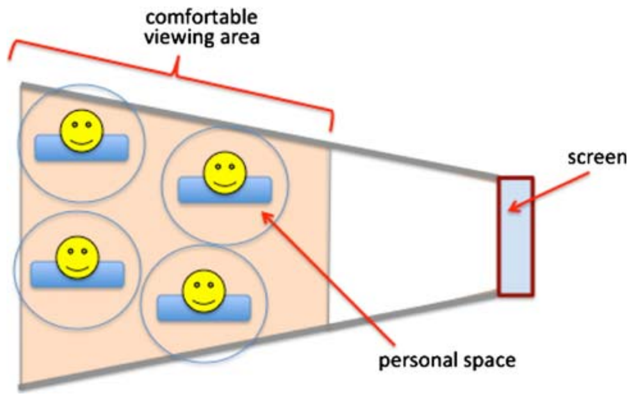


Fig. 1 Comfortable viewing area versus personal space versus screen size

5 Attributes of multi-person-display ecosystems

Based on the considerations above, we then describe two attributes for the description of ecosystems of coupled displays in which people interact

- The scale of multi-person-display ecosystems
- The nature of social interaction.

5.1 Scale of the ecosystem

As anticipated, the scale of the ecosystem depends on the size of the largest coupled device itself. So a perch scale ecosystem tends to be based on yard sized displays (e.g., interactive tabletops coupled to large walled displays in an interactive room [25]). Clearly, there will be exceptions to this guideline. A mobile phone has a very small viewing angle because the eye cannot focus closer than a person accommodation distance, which varies from 7 cm to 200 cm over the course of a person's life. So people always use it at foot distances from the viewer and not inch ones although when in concert with other inch displays they may be at inch distances from one another. Another example is when people are 'inside' the space of the display, i.e. when you cannot see it all in one view (as in i-Land [44]): In this case the size of display and size of the viewing space are similar (in i-Land both at perch scale). Besides, the position and orientation of displays can affect the scale of the ecosystem: if the same two displays are aligned along one surface, or are facing each-other, or have different orientation (e.g. one is horizontally and the other one is vertically mounted on the wall), they create different types of ecosystems, implying different human movements for interaction and affording different social contexts. Nacenta et al. [32] look at this specific issue for adapting the interface to the users' perspective in multi-display environments. The issues of visual angle and orientation in groupware are also treated in [22, 41].

In the following we provide some examples to clarify the size of the multi-person-display ecosystems.

5.1.1 Inch size ecosystem

An example for inch size ecosystem is two Tamagotchi connected by Infra Red [28]. In this ecosystem users can play games, exchange gifts and even have Tamababies if the connection goes well. In inch size ecosystems the users do not need to move their eyes to read the information from one display to another. This is often determined by the fact that either the displays are spatially arranged in an independent manner (e.g., in mobile games such as the invisible train [48]), or that the displays have an inch size and are located in proximity to each other (e.g. GeneyTM [12]).

5.1.2 Foot size ecosystem

In foot size ecosystems the display surface requires the users to move their eyes. Examples of this include the coupling of displays in ConnecTable [47] or Tablet PCs in Hinkleys' Bumping and Stitching techniques [19, 20]. The displays are arranged on the same focal plane so as to create an extended interactive surface, which asks for users to skim a larger real estate without changing the direction of focus.

5.1.3 Yard size ecosystem

In yard size ecosystems users need to move their head to view the coupled displays. This is the case with several interactive rooms in which displays of different orientation are coupled, thus requiring the change of focus. Examples of this include UbiTable [42] and the Dynamo [23] system, which combine personal devices as well as tabletops to a large vertical display. UlteriorScape utilises multiple projectors and Lumisty film to enable a shared display to be coupled with small view dependant screens [26].

5.1.4 Perch size ecosystem

Perch scale ecosystems are configured so that the users definitely need to move their head from one display to another one for interaction, and often their bodies as well. Examples of this include the Stanford iRoom [25] and the i-Land project [44], where several displays, in different scales, are coupled and distributed within a room, and the users act and move within such a dynamic geometry of interaction. In this sense, the space can be considered as a transducer of the interaction.

5.1.5 Chain size ecosystem

Chain size ecosystems imply that users need to move their body to interact with and visualize the displays. Current examples of these displays are often loosely linked spatially. An example of this is the Blinkenlights installation [10]. From their mobile phone, users could send animated images as well as play Pong on the façade of a building whose windows were illuminated (cf. Sect. 4.1) (Table 2).

5.2 Nature of social interaction

Coupled displays may be used in many social situations. At one extreme is a face-to-face meeting with a single colleague, for example, to exchange an image (the *one–one* type of interaction). In contrast, many of the scenarios of use for research systems assume a larger group collaborating around a display table or large shared screen. We will refer to these as the *few* (approximately three to nine people). When displays are positioned or used in a public or semi-public setting, which tends to be the case with perch and chain scale ecosystems, there is also the possibility of a larger audience or more loosely interacting group, which we will refer to as the *many* (more than ten people). In the case of a large public audience, they may also differ in terms of their level of awareness of the displays themselves or that interaction is occurring. These different levels of engagement are discussed in more detail elsewhere in both artistic performance settings [15] and relating to phone-large screen interactions [16].

Applications and situations vary as to whether there is symmetric or open access to the displays, and in particular the largest displays in the ecosystem, or whether one or more participants have privileged access for some period. We use this to distinguish five categories of interaction and sharing.

5.2.1 One–one

This is the simplest case where two colleagues or friends exchange files or images, play a game or otherwise collaborate. An example of coupled displays supporting such a kind of social interaction is the UbiTable [42], which allows participants to link their laptop or tablet computers to a shared horizontal display. The physical size of the table (small end of yard scale) meant that it was ideally suited to one–one interactions and all images and scenarios used in the work are in this category.

5.2.2 One–few

In many presentation settings a single presenter is addressing a small group. In even simple PowerPoint presentations, we see coupled displays as the presenter uses a laptop or podium computer (foot scale) showing a presenter's view of the slides while the audience see the current slide projected on the screen (yard or maybe perch scale). More sophisticated coupling can be used in one–few situations; for example, Pick-and-drop [36] could be used to interact with an electronic whiteboard.

5.2.3 Few–few

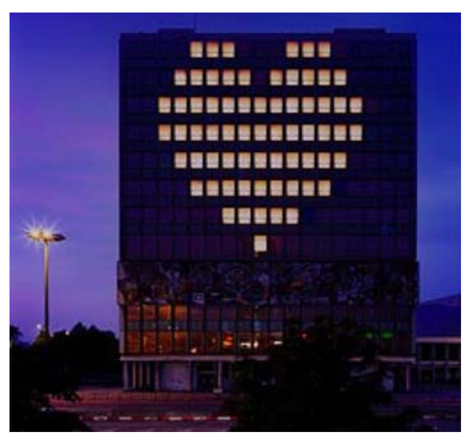
Multi-display systems have long been used for group work or meeting collaborations. Colab [43] is an early example for this: it allowed multiple users to edit and annotate a screen image shared between individual displays and a large projected display. This work demonstrated how social protocols managed many of the apparent problems of contention that arise. A more recent example in the meeting/collaboration setting is WeSpace with support for multi-user and multi-surface interaction [24]. In such settings techniques such as hyperdragging allow users to move objects fluidly from laptops and other devices to table and wall displays [36]. Relate [18] is another technique to sense the relative location of participants' laptops within a meeting room in order to present a spatial view of the people and their devices. IMPROMPTU [8], presents a series of visual widgets to provide access to a user and spatial view of a multi-device workspace.

5.2.4 One/few–many

The most frequent current use of very large displays is at open-air events where a small number of people control what is shown on the public screens. More open installations have allowed members of the general public to act as the 'one' in control. For example the 2006 Six Nations Championship virtual rugby ball and BBC Big Screen [6] or the phone-building pong game in Blinkenlights [10]. In both of these examples, anyone could participate but the nature of the physical space or the game meant the participation was limited at any moment (one person for the virtual rugby and two for Blinkinlights Pong).

Various forms of digital graffiti or electronic post-its do allow participants to use their mobile phone to leave virtual messages or images in the environment to be viewed by others later, for example, the Branded Meeting Places Project allows users to attach annotations to places using their mobile phone's camera and image recognition [11]. While most of these use personal displays on a sequential basis, others use public screens so that this shared digital content is immediately visible, for example in the Wray Photo Display villagers and visitors can upload photos from their mobile phone to a public display in the village post office [45].

Table 2 The scale of people-display ecosystems

Scale	Example	Related work	Picture
Inch	PDA-PDA	GenyTM [12]	
Foot	Tablet–Tablet	Bumping and stitching [19]	
Yard (yd)	Wall Display-PDA	Dynamo [23]	
Perch (5.5yds)	Tabletop–Wall display–PDA	i-Land [44]	
Chain (22yds)	Mobile-building wall	Blinkenlights [10]	

5.2.5 Many–many

In some systems many people can interact with the same public screens simultaneously. For very large installations, this often uses phone-based interaction (e.g., [10]): regrets allowed people in the Cambridge Market Square to text their life's regrets to see them appear (anonymously) on a large public screen [30]. A more strongly coupled example is *tune_eile* which is a table top application designed to be installed in a public space and allow passers-by to share their electronic music collections [33] (Table 3).

6 Relating the scale of the ecosystem to the social interaction space

Different sizes of ecosystems can better accommodate different contexts of social interaction. A foot scale display creates a yard scale ecosystem allowing one or two viewers; a yard scale display creates a perch scale ecosystem allowing up to a small group of 3–9 viewers (*few*); perch scale displays may allow 10–100 viewers (*many*, e.g. a classroom or an academic aula); and chain scale ecosystems may allow many hundreds or thousands.

Table 4 shows examples of systems based on scale of ecosystem and style of social interaction. This natural relationship between scale and social interaction means that the central diagonal is well populated but there are few, or extreme examples in the top-right or bottom-left corners.

6.1 Inch and foot scale

The relatively few examples of inch scale ecosystems are all in one–one social settings, as they require heads to be bent close together to see the displays, for example GeneyTM [12]. At this scale even the interaction of three people is difficult, as one person would see the displays side on or upside down.

This sort of huddling is just possible at foot scale allowing one–few or few–few interactions as seen in the coupling, coordination and negotiation in the proximity regions around mobile devices in [27]. This scale of interaction remains very intimate. An example of few–few interaction with a foot scale ecosystem is in Savannah [17]. This involved children with GPS-enabled PDAs playing a wide game in a chain-sized playing field.

It is physically impossible, even for short periods, to get many people heads together at an inch, foot or yard scale, so the cells in the bottom left corner are completely blank. However, small group interactions at this scale may of course contribute to larger display ecologies, for example, television presenters using technology together (yard scale) which is then broadcast (much larger than chain scale), or one–one encounters in wide games similar to Savannah.

6.2 Yard scale

Yard scale ecosystems are ideally suited for one–few and few–few interactions around electronic whiteboards or digital tabletops. In some cases, especially in formal meeting rooms such as Colab [43], or offices with electronic walls such as i-Land [44], the scale of the ecosystem may be in the smaller perch scale, with broadly similar styles of interaction.

Yard scale ecosystems and displays may also be used for one–one interactions, but the greater distance between the participants allows some degree of privacy especially when combined with personal devices. UbiTable [42] is a good example of this: While the tabletop display used in UbiTable would allow more than two participants, the software divides the table into halves deliberately creating a social situation where there is a personal (but viewable) and a public space.

6.3 Perch and chain scale—one/few–many

Even smaller perch scale ecosystems are too large for effective one–one interactions, bringing to mind scenes in films where an upper-class couple share breakfast at opposite ends of a long dining table. We could imagine exceptions to this general rules, such as forms of scientific visualization where a couple of scientists gather over calculations on small displays and then see the results displayed on a gigapixel wall.

The perch scale and chain scale allow various forms of one–many or few–many lectures, demonstrations or broadcasting. While there may be asymmetric access to the largest display by the few, this does not preclude the many having some level of more private interaction with their own display devices; for example, in the early versions of Classroom2000 (now eClass) Apple Newtons were used by students to make personal annotations on the lecturer's electronic slides [1].

The sending of text messages to Blinkenlights [10] or Regrets [30] is also in this space and, as previously noted, straddles the boundary between one–many and many–many interaction styles as everyone has access in principle, but only the output of one or a few can be seen at once. This highlights the intrinsic problem of many–many interaction, that even with the largest physical display space, the available resolution is still no greater than a single TV or laptop display, hence the individual contributions of only a few can ever be visible.

Table 3 The nature of social interaction

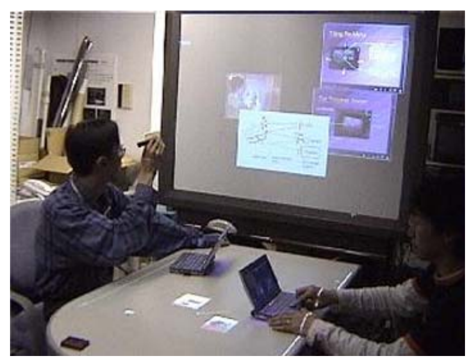
Scale	Example	Related work	Picture
One–one	Face-face meeting between 2	UbiTable [42]	
One–few	Presentation in meeting room	Pick and Drop [36]	
Few–few	Around the table meeting	Hyperdragging [37]	
One–many	Leaving digital post-its on public displays?	Village Photo Display [45]	

Table 3 continued

Scale	Example	Related work	Picture
Many–many	Sharing music in public	Tune_eile [33]	

Table 4 The relation between the attributes of multi-person-display ecosystems

Social Interaction	Scale				
	Inch	Foot	Yard	Perch	Chain
One–one	GenyTM	Bumping and stitching	(Allows privacy) UbiTable		
One–few			Pick and drop		
Few–few		Proximity Regions, Savannah	Dynamo	+i-Land	
One–many					Blinkenlights Regrets
Many–many				Tune_eile	UniVote

6.4 Perch and chain scale—many–many

Many–many interactions at perch/chain scale are possible in a number of situations:

(a) on a serialized basis (as in SMS to Blinkenlights) or music sharing in Tune_eile [33].

(b) where individuals or groups can see and interact with some fragment of a large virtual space, as is the case with many PDA-based wide games. The Pirates! game is a good example of this [9], as it turned the physical space of the HUC2k conference into a virtual ocean with islands, but allowed spontaneous sea battles between proximate users.

(c) where only some aggregate effect of the interactions of the many is displayed in a shared form. For example, the UniVote interactive public voting system, which was implemented at the Lancaster University, in the UK, allowed polls where users could vote using a WAP interface on their phones and see the results appear as a bar chart on public screens in real-time [13].

The last of these reminds us of the need for some means to limit potentially offensive, or merely irritating, interactions on any large public screen. In the case of most text-to-screen projects there is some form of moderation. In other cases, such as UniVote, the interaction is limited to a prescribed form so that the results fit within pre-orchestrated bounds.

6.5 Perch and chain scale—one/few performance

The final part of the design space in Table 4 is the top right corner of one/few interactions in large perch/chain scale ecosystems. The physical size of such an ecosystem means that the results of one–one, one–few or few–few interactions would typically be visible to a public audience. One can think of all this area as 'performance' kind of social setting, as installations that have this nature are typically creating some form of artistic or entertainment performance. The Blinkenlights Pong is exactly like this: While it could be seen as one–one interaction in a chain scale ecosystem, in fact the purpose is not to fulfill the personal work/leisure goals of the few, but to make an impression on the many. One envisaged scenario is of a multiplayer 'shoot 'em up' game where each of the (few) players sees a heads-up display on their mobile phone, but where a public screen shows an overview of the game area, together with high-definition images of the hot spots; thus the shared large display would form part of the game play for the players and be a sort of live 'digital sports' coverage for the audience.

6.6 Different scales during social interaction

The above discussion highlights in several places the need to think carefully about multiple interacting scales:

(a) the scale of individual displays and devices,
(b) the scale of the physical people-display configuration that we have called ecosystem,
(c) the scale of the physical space in which this is set,
(d) the scale of the space for social interactions around those devices.

We have said that (b) is typically one size larger than the largest display (a). In some of the examples, such as a meeting room, the physical space (c) is the same as the ecosystem (b). However, we have seen some examples where the display ecosystem is set within a larger physical space: an information kiosk in a train station, phone image sharing in the open, catching prey in Savannah, or using the UbiTable in a public space.

The social interaction space (d) is limited by the available physical space (c), and is typically similar in scale to the ecosystem (b), but may also be either smaller or larger. In the case of inch scale ecosystems the actual social space is at least a few feet across including two heads and shoulders. The larger scales of ecosystems may have smaller group interactions within the space. In such cases, if the larger display is part of the interaction then we tend to get audience/bystanders as well as participants, so arguably the social interaction space is still in the scale of the ecosystem.

These observations show that the scale of the displays and the ecology they create is intimately connected with the forms of individual and social interaction that are possible, or at least natural. The ways in which displays can be coupled are very diverse though, and do not necessarily require proximity. Put differently, the scale of the physical space can have a different relation to the social interaction space depending on the type of coupling interaction.

7 Ecosystem binding and social context

There currently exist a range of *interaction methods* for binding two or more devices together. These methods can be either single-person or multi-person and can often be appropriated for multi-person-display ecosystems binding. All of the methods described rely on a combination of software components and hardware sensor technologies. We first consider a range of interaction techniques and then discuss how they may be more or less appropriate depending on the social setting.

7.1 Interaction methods for binding

Any type of physical artifact including a display can be instrumented with sensors. Many small devices with displays (phone, PDA, tablet and laptop) are already equipped with short- and long-range radio technologies including Bluetooth, 802.11, Infrared, GPRS, 3G and GPS. These are radio systems, which in addition to their communication roles can act as sensors. Collectively, such sensors can provide accelerometer, location, physiological, proximity and signal strength data. In order to orchestrate and control the communication among the different networked sensors, different interaction techniques are possible. These are described below in relation to the human body action used to perform the binding and summarized in Table 5. These classes and respective sub-classes are not fully mutually exclusive; instead this table can be used as a reference when considering different binding techniques for the design of a particular ecosystem.

7.1.1 Synchronous human movement

The first class of interaction method relies on synchronous human movement. Body movement with a device can form an input that can be interpreted as a gesture such as shake, bump, tap, bounce or rotation.

ConnecTable relies on the simple physical movement of two displays towards each other at the same time to temporally create a shared display area combining the two previously personal ones [47] and is shown in a one–one social context. SyncTap uses a simultaneous button press method to authenticate and couple displays into an ecosystem [38]. ProxNet again uses a button push but relies on the devices being in close proximity so the shared radio spectrum can be surveyed and matched [39] and is shown in a few–few social context. Smart-Its Friends and Shake Well Before Use rely on a single user simply holding two devices together and shaking them to provide a method for automatic authentication [21, 29]. While using accelerometer data for secure device pairing, this may provide a simple and familiar method for inch scale ecosystem formation. The synchronous gesture of bumping two tablet PCs together is demonstrated in [19] to temporarily form a larger display ecosystem and is shown in a few–few social context. In Touch-And-Play (TAP) the physical act of the

Table 5 Interaction methods and their sub-classes of display ecology binding with examples

Interaction Method	Sub-class	Examples	Ecosystem scale shown	Social context of examples shown
Synchronous co-located human movement (SHM)	Movement towards	ConnecTable [47]	Foot	One to one
		Sensed Proximity Regions [27]	Foot	Few to few
	Button	SyncTap [38]	Upto Yard	One to one
	Push	ProxNet [39]	Upto Perch	Few to few
	Shake	Smart-Its Friends [21]	Inch	Personal (suitable for one to one)
		Shake Well Before Use [29]	Inch	Personal (suitable for one to one)
	Bump	Tablet PC bumping [19]	Foot	One to few
	Touch	Intra-Body Comms [52]	Yard	One to one (Card exchange)
Continuous action (CA)	Point Tap	Pick-and-drop [36]	Foot/Yard	One to one
	PointRight	iRoom [25]	Perch	Few to few
	Gesture	Snarfing [31]	Chain	One to few
Action & Infrastructure (A&I)	Stroke	Stitching [20]	Foot	One to few
	Alignment	Point & Shoot [4, 5]	Yard	One to few
	Request	Bluetooth Proximity Regions [27]	Foot	Few to few
		UbiTable [42]	Yard	One to one
		Pong [10]	Chain	Many to many
	Map	iRoom & iRos [25]	Perch	Few to few
		Relate [18]	Perch	Few to few
		IMPROMPTU [8]	Perch	Few to few
	Placement	BlueTable [51]	Yard	Few to few
	Tokens	TranSticks [3]	Perch	Many to many

person touching two devices causes the displays to form an ecosystem [34] using the person's body as the transport medium for the signals between the devices. Extensions of this with physical handshakes could support few–few social context multi-display ecosystem formation.

7.1.2 Continuous action

The second class of interaction method relies on an action or series of continuous actions between the displays to form an ecosystem. Here body movement with a support device such as a pen or sensor can form an input that can be interpreted as a binding gesture.

Pick-and-drop relies on a special physical artifact, a pen with a unique ID [36]. This allows users to pick up items on one display by tapping and holding a button and then to move it to another display and is shown in a few–few social context. Snarfing is a technique where a laser pointer is used only to indicate the area of interest, and the contents there are copied to the handheld [31]. With snarfing, the binding is implicit. A stitch is a spatio-temporal gesture that starts on one device display and ends on another which is aligned with the first [20]. Here the displays act as a larger work surface with the addition of interface elements that are multi-display aware. Point & Shoot is a method for forming a display ecosystem between a large situated display and a mobile phone [4, 5]. Visual codes are used to determine both phone position with respect to the larger display and also a bluetooth password to use to initiate a connection.

7.1.3 Rich fixed/ad hoc infrastructure

The third class of interaction method relies on explicit user action followed by infrastructure support binding devices and their displays into an ecosystem.

The iRoom represents a heavily pre-configured display eco-system that a new display can minimally couple to via the iCrafter system in the iRos operating system [25] and is shown in a few–few social context. A map or controller interface displays the geometric arrangement of screens and lights in the room allowing application level coupling or end user coupling to occur. Other systems, such as ARIS [7] and WIM (World in Miniature) [50] also use map-like or geometric views of displays within displays (in the former iconic, in the latter as facsimile miniatures), but for configuring applications once the displays have been coupled by other means.

The UbiTable allows users to couple laptop computers with a large shared interactive surface (DiamondTouch) [42]. Relying on a close proximity to communicate on IR then switching to wireless, the UbiTable couples personal record space on the laptop display with a mirrored space on the surface. BlueTable couples small mobile devices that have screens and wireless connections, with larger interactive surfaces [51]. This display ecosystem is formed using a computer vision based handshaking method. Here the interactive surface forms an extended interface for the mobile device along with the system tracking its location on the surface. TranSticks are physical tokens for virtual connections where a user places a memory-key or memory-stick into the appropriate reader in each device [3]. The sticks have a shared data space that can be rendered as a shared display between the two devices and displays and is shown in one–many and many–many contexts.

7.2 Ecosystem binding for social contexts

Table 6 locates several of the coupling techniques described within the same social/scale diagram as Table 4. We can instantly see some patterns. The blank space at the lower left is explained by the fact that there are few multi-display ecosystems in this portion of the design space as discussed in Sect. 4. On the whole more infrastructure techniques are used at the larger scale and more physical/movement based techniques (SHM & CA) at the smaller scales, reflecting the difficulties of traversing large spaces, moving or otherwise directly manipulating large displays and involving large numbers of people in movement based activity.

As noted, there are many forms of multi-display systems both wired and wireless that weld the displays into a fixed ecology suitable for a single purpose use. Many of the binding methods described in Sect. 7.1 are not attuned for multi-person-display ecosystems such as Shaking or Pong while others such as Stitch and UbiTable are. The fluid middle of our design space requires support for connections that are spontaneous and for ecosystem formation that lasts as long as the real-world activity (meeting, conversation, game, etc.) requires it.

Table 6 Relationship between social interaction support and multi-person-display ecosystem scale

Social Interaction \ Scale	Inch	Foot	Yard	Perch	Chain
One-One	Shake	Connectable, UbiTable	Touch/Push	Proxnet	Pong
One-Few		Bump	Point& Shoot	Map	
Few-Few		Stitch	Point-Tap, BlueTable	Proxnet	
One-Many				TranSticks	Pong
Many-Many				TranSticks	TranSticks

It is clear that the infrastructure-based techniques can be used in any social and spatial setting. They are very generic, but involve less direct physical actions. Other interaction techniques depend on more physical or direct coupling and so it is interesting to consider how they may perform in the different social settings introduced in Sect. 5.2 (which loosely correlate with size of ecosystem).

7.2.1 One–one

The exchange of business cards using IR or Bluetooth is classic examples of one to one social interaction with multiple loosely coupled displays. From a research perspective this section of the design space for both ecosystem formation and interaction is well researched. Translating these methods which are technologically sound into interaction styles people would be comfortable using in day to day one on one social settings requires further HCI research and careful interaction design.

One issue is related to the level of intimacy required by different techniques. Most require a level of proximity, but not more than would be normal in one–one conversation. However, Touch-And-Play (TAP) [34] is a more intimate form of connection (as would be any technique using personal area networks, or other physical contact). There are formalized situations where we accept physical touch, for example, a handshake, but new social conventions would be required to allow a business contact to touch one's phone or PDA to establish a link.

Some forms of interaction seem potentially damaging (e.g., bumping or shaking) and again it may require a level of mutual trust to let a stranger bump their mobile phone against ones new tablet PC.

7.2.2 One–few

In one–few social settings, the display ecosystem methods for both Chain and Inch have not been explored. Clearly the ability to form an inch scale ecosystem suitable for interaction is limited by the physical setting.

A one–few interaction may often involve the presenter taking up a physical location close to a large (Yard or Perch) screen. In such cases techniques that involve some form of synchronous human movement or continuous action are possible between the large screen and presenter's own personal device; for example, tapping, or touching the displays.

Where the 'audience' or listeners (the few) also have displays they wish to join to the ecosystem (e.g., to share personal notes), then it would also be possible for them to use these physical means of connection on a one-by-one basis either to the larger display or to the presenter's display device.

7.2.3 Few–few

Some of the techniques using simultaneous human movement or continuous action are possible for small numbers of participants; for example, in Savannah simultaneous button press is used to 'attack' prey in the game and it would be possible to use similar techniques for coupling. However, these become cumbersome as the number grows beyond two or three participants and so is perhaps only suited for games or playful interaction.

For larger groups one can envisage paradigms where one or two people initiate an ecosystem, using any form of one–one coupling, and then others join by coupling with existing members of the ecosystem, rater like the situation described for one–few interactions.

7.2.4 One–many

In large lecture theatres or outdoor settings, this situation is similar to that described for one–few interactions, except it is likely that any form of large shared display is out of reach (Perch or Chain sized display). However, in such cases there is often the possibility of some form of control location such as a lectern in a lecture theatre and forms of physical coupling can be used either simply plugging in a personal device, or by using one of the SHM or CA techniques with a token at the lectern.

If the audience need to connect displays then 'contagion' techniques such as those described for few–few interaction are possible: rather like passing a pile of notes back through a lecture theatre, the presenter can touch, bump or otherwise connect to a few people near the front and then this can be passed back through the crowd.

7.2.5 Many–many

In this case, and also in the one–many situation if the audience wish to connect their own displays into the ecosystem, simply having large numbers of people troop to a shared display or control location will usually be impractical. Infrastructure approaches, which are possible at all scales and situations, come into their own and many of these can be applied at this large scale; for example, URLs or other text tags to be typed in, visual codes, and image recognition. However, if more physical or direct interaction is desired, in a game for example, then 'contagion' techniques can again be used.

In this section, we have discussed situations where there is at most one large display and none of the coupling techniques we have reviewed so far have been applied to couplings of larger displays. This is partly because larger displays are typically fixed within their environment and likely to have hard-wired couplings. However, there are circumstances where groups may want to connect public display, for example, in a bar setting linking a wall display and tabletop display. The emergence of micro-projectors that can be embedded in mobile devices opens novel interesting possibilities for the design of coupling techniques for larger, mobile displays.

8 Conclusions and open discussion

In this paper, we have provided some criteria for critically approaching the design of multi-person-display ecosystems, in which multiple displays are coupled. Our approach has considered physical constraints, human focus of attention, social context and type of body movement/ interaction. This allows for the description of the design space independently from the different technical implementation solutions for a coupling mechanism. This exercise has provided some insights that we feel are relevant for the designers of multi-person-display ecosystems:

- we have shown how the scale of each single display has an impact on the scale of the ecosystem and on the scale of the social interaction space. In this sense, the physical space still has an impact on the social affordances of the ecosystem, as in the case of single displays. However, as a result, the geometries of interaction become more complex and dynamic;
- the scale of the ecosystem tends to create 'natural' levels of interaction, with one-to-one sharing principally at foot/yard scales, one–few and few–few sharing at yard or smaller perch scale and one–many and many–many at perch/chain scale (as shown in Table 4);
- to some extent, the type of coupling technique, distinguished in terms of human body movement, can affect the natural relationship between the scale of the ecosystem and social interaction. In particular, according to the type of coupling technique, interaction geometries can become dynamic and be more or less suitable for specific types of social contexts (e.g. gaming, performance, presentation…). For example, note that in Savannah [17] the inch scale and foot scale ecosystems are dynamically formed and reformed for short periods. This appears to be a pattern for a genre of ecosystems where chain scale wide games or serious pursuits are performed using digitally connected individual displays interspersed with short periods of heads-together interaction over closely coupled display ecologies at the foot or yard scale.

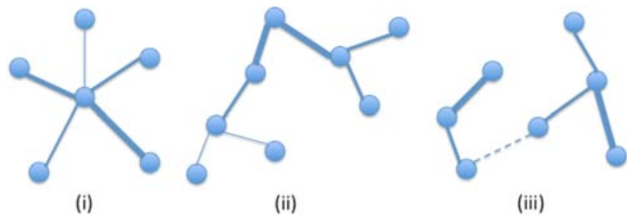


Fig. 2 Contagion-based coupling building on one–one couplings: (*i*) hub-and-spoke, (*ii*) spreading from single source, (*iii*) spread and merge. In all cases the *thicker lines* denote earlier couplings

Thus, understanding and ordering the dimensions that affect such geometries of interaction, i.e. scale of the ecosystem, nature of social interaction and coupling interaction technique, can help to approach the design space in a more informed manner. Clearly, other aspects including duration and parallelism versus serial interaction need to be considered, although these were not in the focus of this paper. We have seen how in general synchronous human movement and continuous action are ideally suited for one–one couplings but can be extended to create more complex ecosystems using forms of 'contagion' where a series of one–one couplings gradually builds up a larger group of coupled displays. For ecosystems involving small numbers of people and devices, then patterns where there is a single individual or display (e.g. a public screen) which acts as a hub to which all other displays connect (see Fig. 2i) tends to emerge. Where the number is larger, more complex patterns are needed using indirect connections. In one–many situations or where the interaction is focused on a single display, this is likely to start with a single individual or display and then spread outwards (Fig. 2ii). Where there is no obvious leader or focus, then ecosystems may grow from several initial seeds with groups of connected displays merging through one–one couplings (see Fig. 2iii). We expect that such considerations in time can inform future work for the characterization of the taxonomy.

By looking at the coupling techniques at the pragmatic level, i.e., how they imply people's movement, focus and spatial arrangement—we can assume a user-centered perspective to analyze and design multi-person-display ecosystem which consider the specific task and social context.

Consider for example, multiple users who are willing to share on an interactive tabletop some of their personal contacts stored in their mobile devices. In this context, it makes sense to think of touch and proximity between private and shared displays as a way to preserve a sense of physical ownership and control of information and interaction. Here, the mobile device serves as a token or personal handle to private information.

By contrast, the distribution of sensors in different displays allows for interaction capabilities in a broader variety and scale of environments, which, as represented in Table 4, open possibilities for social interactions in perch and chain ecosystems. In these contexts, coupling and interaction techniques, which are based on the infrastructure and gestures in 3D, for example, can support novel forms of computing in public spaces, which deal more with performance and social engagement rather than personal information management. In such scenarios, the possibilities to break free from the spatial constraints of touch and proximity can afford more dynamic and elastic geometries, which are often suitable for applications such as mobile gaming, for example.

It is clear that as designers of such geometries we need to tailor the different parameters, i.e., scale, social context and coupling techniques, according to the type of experience we want to support. While doing this, we also need to consider the culturally differences (e.g., eastern and western) and fast changing social protocols and practice, and how these can be supported, affected, or revolutionized by technology.

Users of personal displays and public displays currently have no expectation that their devices can seamlessly couple as required to complete a particular task. However, it is clear that this will change both due to the proliferation of small personal devices with limited screen space and also large public displays. The challenge for designers is to develop both the systems for such coupled display ecosystems while understanding their social context of use.

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