Privacy in Location-Aware Computing Environments

This study explores how privacy preferences vary with place and social context. These findings are useful for designing privacy policies and user interfaces for pervasive computing.

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The boundary between cyberspace and physical space is fading. Location-aware technologies, such as sensor networks, enable everyday devices to become increasingly, and often invisibly, interconnected with one another and with the Internet. Some analysts predict that by 2010 half of all cell phone users in the US will be using location-based services.[1] Today, users struggle to maintain the security of their individual computing devices and have difficulty managing their privacy online. Tomorrow, these challenges might be unimaginably complex, as location-aware technologies embedded in both devices and environments reveal not only personal information but also location and context information.

The way users think about these more complex privacy issues and how they attempt to manage them have implications for the privacy and security of persons, places, and systems. Research concerned with privacy in location-aware technologies often focuses on systems and software for privacy policy management.[2–4] As with much new technology, however, users' interests and concerns (particularly regarding privacy and security) are not always reflected in the design of new technologies.[5,6] As a result, people often use new technologies in unforeseen ways,[7,8] which could compromise privacy and security.[9]

We have conducted a study, using the experience sampling method (see the sidebar), in which we observe 25 users, all undergraduate students, for one week to examine their willingness to share location information in various settings and with different requesters. ESM lets researchers observe actors in situ over time. We also investigated whether willingness to share location information varied depending on who was seeking the information.

Other studies of how users respond to location requests have specified the requester by relationship and role or by name.[10,11] For example, Sunny Consolvo and her colleagues found that the person requesting location information (for example, spouse, coworker, or boss) influences user willingness to share in different situations.[11] Here, we use broader categories of requesters rather than specific named individuals or specific relationships. An advantage of these more open-ended categories is that they can better exploit the capabilities of some ubiquitous computing systems—for instance, environments with embedded sensor technology could capture location information, or even more complex social context information, that can be transmitted broadly to anyone requesting information about that place or about the users.

Place and social context

In our study, we are interested in users' privacy preferences according to *place*. As sociologists

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The Experience Sampling Method

Diary methods are a group of research tools and methods used in psychology for "documenting the particulars of life."[1] The distinguishing feature of a diary method is that participants self-report their own ongoing experiences. This feature enables the recording of events and experiences in a more natural context than a formal interview. Diary methods fall into three categories: *interval contingent* (where participants report at regular intervals), *signal contingent* (where participants report when they receive a signal), and *event contingent* (where participants report whenever a defined event occurs).[2]

Within the broader category of diary methods, the experience sampling method (ESM) has emerged as a popular method for evaluating user experiences and situations.[3] In an ESM study, also called an ecological momentary assessment, participants fill out a questionnaire several times a day. The questionnaire asks about their current activities, conditions, and feelings. A typical ESM study is signal contingent, involving seven signals a day over seven days. Christie Napa Scollon, Chu Kim-Prieto, and Ed Diener presented a survey of how researchers have used ESM to evaluate a wide variety of experiences.[4] In particular, some researchers have used ESM to evaluate communications technology: Robert Kubey, Reed Larson, and Mihaly Csikszentmihalyi surveyed communications-related ESM studies such as television viewing.[5] Sunny Consolvo and Miriam Walker used ESM to evaluate user experiences with the Intel Personal Server ubiquitous computing device.[6]

As in our study, technology can improve ESM methodology. Instead of using a notebook or paper questionnaires to record responses, Leysia Palen and Marilyn Salzman ask their participants to record voicemail messages upon receiving an alert.[7] Another common electronic ESM tool to use for questionnaires is a PDA,[8] and more recently a mobile phone.[9,10] Our study is similar to that of Jon Froehlich and his colleagues,[10] in that we combine event- and signal-contingent alerts (although this article concentrates only on results from our signal-contingent alerts). On the other hand, we chose not to use such technology for recording responses, but we combined the traditional notebook with network monitoring to better interpret the data we collected.

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and other social scientists explain, place means more than simply space or location. According to Thomas Gieryn,[12] place has three necessary features: geographic location, material form, and cultural meaning. The last of these indicates that social actors understand what types of behaviors are expected in particular places. That is, people invest certain values and meanings into particular spaces. For example, different behaviors are expected in a bar than in a place of worship. Moreover, people might behave somewhat differently in different places, even when engaged in the same type of activity—for example, eating at home versus at a diner, or at a four-star restaurant, or in the home of your boss. (A lively debate has emerged about whether cyberspace is indeed a place, since virtual worlds do not have physicality in the same way as a building or park.[12,13] Surprisingly, this debate is an old one, beginning as early as the emergence of the telegraph.[7,14] Use of terms such as virtual world and cyber café, as well as the technical necessities of designing and architecting such spaces, suggests that we culturally interpret many online spaces similarly to how we think about social places.)

Location-sensing technology raises interesting problems for place, such as the expectations users have for privacy in particular places[8] or while engaged in specific activities.[13] But place also raises

Technology for ESM

In our user study on privacy, we issued each participant a pager and a questionnaire notebook. The pager was a Motorola Bravo numeric pager operating in the 406-512 MHz band. To programmatically send pages to the participants, we used an SMTP-to-page (simple mail transfer protocol) gateway operated by the pager service provider. The notebook contained questions about communications use (wired, wireless, and other communications devices), current activities, location, and so forth.

We chose to use a notebook for several reasons: First, our questionnaires were extensive, containing 203 possible questions, including multipart and open-ended questions. So, it would be impractical to fill them out using a standard PDA. Second, we considered using a PDA equipped with an 802.11 network adapter so that we could use the same device for signaling participants, for having participants fill out questionnaires, and for transmitting the questionnaire responses to a central data-collection server to limit the possibility of losing data if not adequately saved on the device. But we rejected this solution, because we would not be able to signal participants when they were out of range of an 802.11 network (for example, if they were off campus). Moreover, participants could not be signaled if the 802.11 network was having trouble, which was one of the aspects that we were interested in monitoring. Therefore, rather than requiring participants to carry two electronic devices (a pager and a PDA), which would only increase the probability of a device malfunctioning during the study, we decided to use a pager and a notebook.

questions for location-sensing technology. For example, is the relevant location information that must be sensed or transmitted the absolute geographic location such as GPS coordinates or room numbers, or is it the socially defined place such as home or work?[11,13] Of course what is considered relevant information will vary according to the person asking and the purpose of the information.[11,13]

Social context is an important aspect of place. It concerns how people define where they are, what they are doing, and who they are with at the time. Our study examines how users' real-time location privacy preferences are associated with their social context within and across specific places.

The user study

In June 2004, we recruited participants for a computer activity study using a Web site and college bulletin boards. The Web site used a registration form to preselect participants (for example, to make sure they owned a mobile wireless device). We interviewed the respondents and selected 30 participants: 15 male and 15 female. All of the participants were undergraduate students (with a mean age of 20). One participant (male) dropped out during the study, and four others (one male, three female) did not answer an adequate number of location requests to be included in the analyses reported here; these participants' data are excluded from the results, leaving a total of 25 participants. We gave each participant a pager and a questionnaire notebook, which they agreed to carry for seven consecutive days (see the "Technology for ESM" sidebar for details). At the end of the seven days, we interviewed and debriefed each participant (and paid them $100 for their time). The study followed a strict protocol approved by the Dartmouth College institutional review board.

Participants provided conflict times, during which they did not want to be paged—for example, when they were asleep or in an examination. Outside these times, each participant received up to seven pager alerts per day at random times. Each alert occurred at least 45 minutes after the preceding alert, to prevent the alerts from being too intrusive. At each page, the questionnaire contained questions about current activities, location, communications usage (wired, wireless, Voice over Internet Protocol, and other communications devices), how many people they were with, and their willingness to share location information. The questionnaire included a total of 203 possible questions per pager alert, but the number of questions varied according to the participant's activities. For example, at each page in which participants reported using an electronic device (any type, though most often participants were using a laptop computer), they were asked whether they would be willing to share their location. The exact wording was, "Which, if any, of the following would you be willing to inform of your current location (for example, GPS coordinates or building name)?"—with the following three categories of responses:

- anyone who asked (yes/no);
- anyone who sent email to you (yes/no); or
- anyone from the list you specified (yes/no).

For the last category, we did not ask them to actually identify specific individuals or relationships, so this category indicates their general willingness to share with particular persons they know. Other research has observed that there is likely variation in sharing across known intimates,[10,11] but we cannot test for such differences here. Instead, we examine differences between this category and the two other categories of more distant requesters. The first category, anyone who asked, was meant to be as open-

TABLE 1
Pages answered and location requests made at various places.

Place during page	Pages answered		Location requests	
	No.	%	No.	% of pages
Home	488	47.6	328	70.4
Work or other	123	12.0	16	12.0
Dining or restaurant	111	10.8	20	18.0
Classroom	73	7.1	15	20.5
Library	69	6.7	53	76.8
Friend's home	65	6.3	29	44.6
In transit	96	9.4	7	7.3
Total	1,025	99.9*	468	45.7

* Total doesn't add to 100% due to rounding

ended as possible, but some participants could have interpreted this category more narrowly to exclude retailers or other institutional requesters. Finally, the question asked about current location and provided GPS coordinates or building names as examples of types of location information. (User preferences can vary, depending on the type of location information disclosed, but we cannot examine those issues in this study.)

We also tracked participants wired and wireless network usage using system log and Dynamic Host Configuration Protocol records, Simple Network Management Protocol polls, email server logs, and network sniffing. (Further details are available elsewhere.[15])

Sample limitations

One study goal was to evaluate how users respond to location-seeking requests during real-world usage. But, of course, our study has several limitations. One limitation is that we asked about willingness to share location information only when participants reported using an electronic device. However, sensor and other new technologies will likely enable location-sensing capabilities regardless of active usage of devices (for example, cell phones have active GPS technology, regardless of usage), and environment-embedded sensors could capture a user's location even when they are not carrying devices. Therefore, our study does not fully capture the entire range of experiences in which location privacy is relevant.

Of course, the most serious limitation of our sample is the use of only undergraduate college students. Clearly, this is not a representative sample of all users, or even of all college students, although few if any ESM studies are representative in a statistical sense because of very small sample sizes. College students have lifestyles and technology-usage patterns that are often specific to this population group. On the one hand, college students' high usage rates of many different technologies and devices, including mobile technologies, could be an important bellwether of the types of privacy concerns and conflicts that might arise as location-aware technologies become more prevalent. On the other hand, college students' apparent willingness to engage in high-risk technology behavior such as password sharing and peer-to-peer file sharing could mean they are far less concerned with privacy issues than are population groups. Future research, including studies of representative samples of the population such as in survey research, must examine whether population groups vary in their concerns about, or willingness to share, location information.

Results

Before detailing the privacy-related aspects of our study, we first describe some of the basic usage patterns we observed from the participants.

General usage patterns

The 25 participants received a total of 1,114 pages over the seven-day study period, or an average of 44.5 alerts per participant—about six pages per day for each participant. Overall, participants answered 92 percent of the pages received (n = 1,025). Reasons for failing to answer a page included sleeping, showering, eating, and forgetting to carry the pager. For nearly half (44 percent) of all pages answered, participants were with other people, most often friends (34 percent).

For 46 percent of all pages answered (n = 468), participants were using some electronic device. The extensive wireless network on campus enables students to be mobile but remain connected throughout the day. We monitored participants' use of the wireless network. In nearly eight of 10 pages in which they were using a device, participants were online (an average of six hours per day on the campus wireless network, with 40 percent exceeding six hours per day). Over two-thirds of participants were mobile on one or more days of the study, where *mobility* is defined as accessing two or more wireless access points (APs) at least 50 meters apart. Mobile participants visited an average of 22.6 different APs during the week. (At the time, the campus network included more than 500 APs.)

Place and technology usage

Participants were more likely to be at home during a page than in any other location during the study. Participants reported being at home for 48 percent of all pages, as table 1 shows. While at home, participants used one or more

TABLE 2
Participants' willingness to share location information at different places, for different categories of requesters.

Place during page	Percent willing to share with at least one requester category*	Percent willing to share with list*	Percent willing to share with email*	Percent willing to share with anyone*
Home	55.2	54.3	10.4	6.1
Friend's home	27.6	28.0	6.9	0
Library	51.0	50.9	37.7	22.6
Other public place	32.8	31.0	13.8	6.9
Overall (regardless of place)*	50.1	49.0	10.0	8.0

* For all percentages, the denominator was the number of requests.

electronic devices during more than two-thirds of the pages (70.4 percent). Although participants answered fewer pages in certain locations such as the library, if they were using a device at the time of the page, they would at least respond to the location-request questions. Thus, participants responded to many location requests in the library, for example, but very few while in transit.

Sharing location information

Table 2 shows participants' willingness to share location information, overall and within specific places. As the table indicates, participants were willing to share location information for half of all requests. Overall, participants were significantly more likely to share location information with people in the list they specified (49 percent) than with email contacts (10 percent) or with anyone who asked (8 percent). The statistical differences for sharing across categories of requesters overall also hold for each specific place. In addition, people were statistically significantly more willing to share with email requesters than with anyone who asked when at home, in the library, or at other public places (statistical results not shown).

When we consider how place is related to willingness to share location information, we find some surprising patterns. The emergence of new technologies for social networking (for example, www.dodgeball.com and www.meetro.com) suggests that when users are out with friends or engaged in social activities, they will want to reveal their location information so that others can join them.[1] Similarly, some research suggests that users are less likely to reveal location when they are at home (versus at work) or engaged in certain types of private or semiprivate activities, such as studying or going out on a date.[11,13]

Our participants, in contrast, were more willing to share when they were at home or in the library compared to when they were in other public places or at friends' homes. Consistent with the patterns of sharing overall, at each place participants were more willing to share with specific requesters on the list they specified than with broader categories of requesters.

Revealed privacy policies

Examining the patterns of sharing location information across the three different requester categories indicates that our participants fit into three types of *revealed location-privacy policies*. We do not use the term *policy* to mean a preset plan in which users choose a privacy setting before usage, which then governs their devices and applications. Instead, given that it arises from the users' actual behavior over time, we use *policy* in a more organic sense to mean the *apparent rule* that participants follow.

The majority of participants in our study had a consistent policy for sharing across all conditions and situations. Nine participants answered no to all location-sharing questions, with all requester categories, every time, so we label them consistent-private (CP) users. In contrast, 10 participants answered at every request that they would share their location with requesters who were on the list they specified. We label this group the consistent-share-with-friends (CSWF) users.

Different from both types of consistent users were the six participants who varied in their willingness to share location information with different requester categories, depending on the situation. We label them variable-privacy (VP) users. Of all the times they were asked to share location information, VP users were willing to share most often with requesters who were on the list they specified (74 percent of all requests), but sometimes they were also willing to share with email contacts (36 percent) or even with anyone who asked (28 percent).

Although the number of participants in each category (particularly the VP category) is relatively small, the policies themselves are based on participants' behavior over a minimum of eight pages per user. CP users had a mean of 19 pages each in which they responded about their willingness to share location information; CSWF users had 17 pages each; VP users had 21 pages each.

Figure 1 shows how VP and CSWF users compare in their willingness to share location information according to place at the time of the request. CSWF users were somewhat more likely to share when at home compared to VP users. Analysis of variance (ANOVA) shows $F = 3.4$, $df = 1$ and 221, and $P < 0.10$, where F is the ratio of the estimate of between-group variance to the estimate of within-group variance,

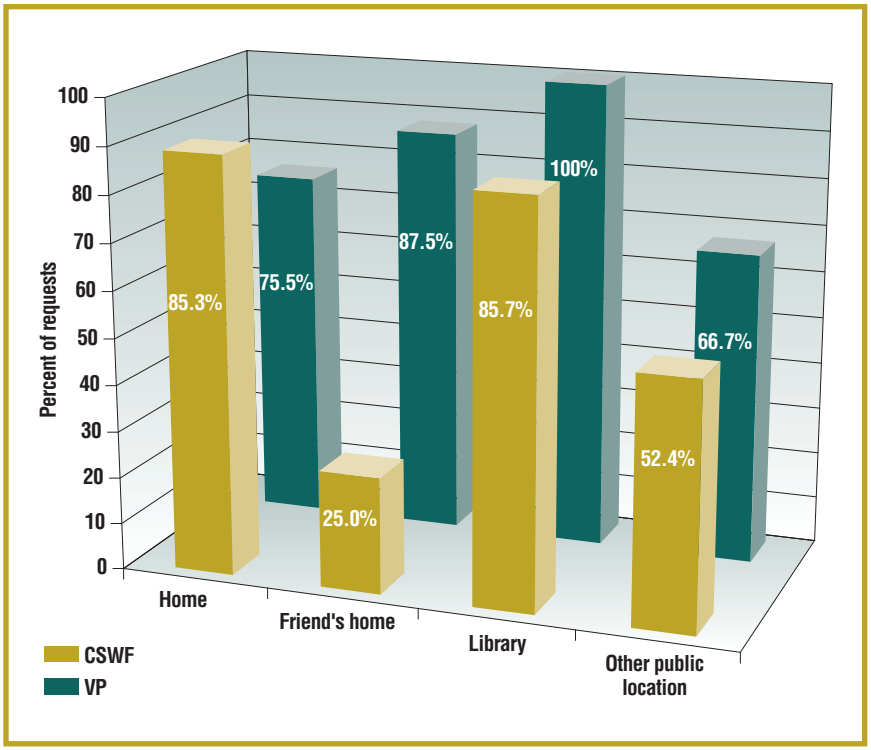

Figure 1. Consistent-share-with-friends (CSWF) and variable-privacy (VP) users' willingness to share according to place at the time of the request.

df is the number of degrees of freedom, and *P* is the significance level. When at friends' homes, however, CSWF users were significantly less willing than VP users to share location information, possibly because they were willing to share only with people on their list and they were interacting with them already (ANOVA: $F = 6.4$, $df = 1$ and 10, $P < 0.01$). Given the small number of cases with which to compare, however, the difference at friends' homes must be considered merely suggestive. There were no statistical differences between CSWF and VP users in willingness to share when in the library or in other public places.

Figure 2 shows the extent to which VP users were willing to share location information with specific types of requesters at different places. VP users were most willing to share with requesters in their list and with anyone who asked when they were in the library—a public space. It is unclear why they were less willing to share with email partners than with anyone when in the library. In contrast, they were most willing to share with email contacts when in other public places, such as restaurants, other public buildings, or outdoor areas. Not surprisingly, VP users were not willing to share with anyone who asked when at friends' homes, possibly to protect their friends' privacy. In contrast, VP users were willing to share with anyone who asked when they were at home in just over 20 percent of requests.

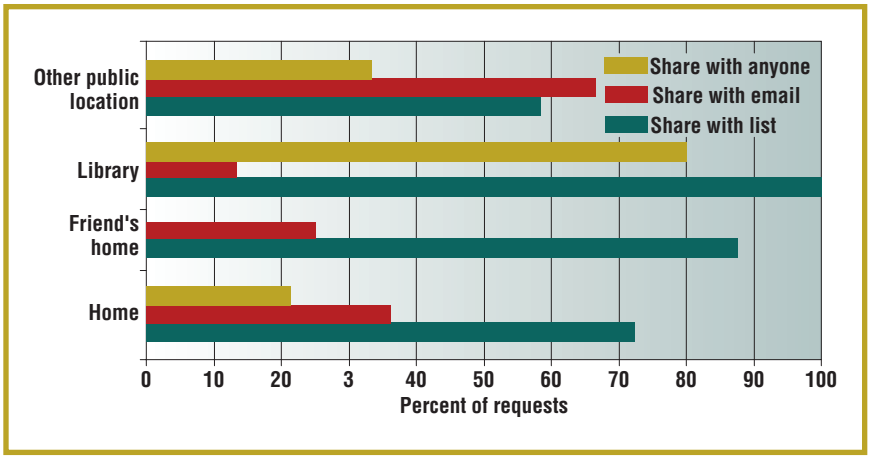

Figure 2. VP users' willingness to share with the three different requester categories according to place.

Location privacy and social context

In addition to the location aspect of place, the social context of place—who the participants were with at the time of the request—also had some affect on their willingness to share location information. Participants were far more willing to share regardless of requester category when they were alone. However, once again, place (for example, home versus a public setting) also mattered, as figure 3 shows. Our participants were less willing to reveal location information when they were with others (typically friends) than when they were alone. The influence of being with friends was statistically stronger when participants were at home (ANOVA: $F = 10.3$, $df = 1$ and 217, $P < 0.01$) or in the library (ANOVA: $F = 5.04$, $df = 1$ and 26, $P < 0.05$). (There was no statistical difference in willingness to share between being alone or with others when they were at a friend's home or at some other public location—but, of course, participants were less likely to be alone in such places, especially friends' homes.) These findings suggest that when participants were alone at home or in the library, they were more interested in enabling social contact—that is, having others find them—and possibly less concerned about privacy, even when they

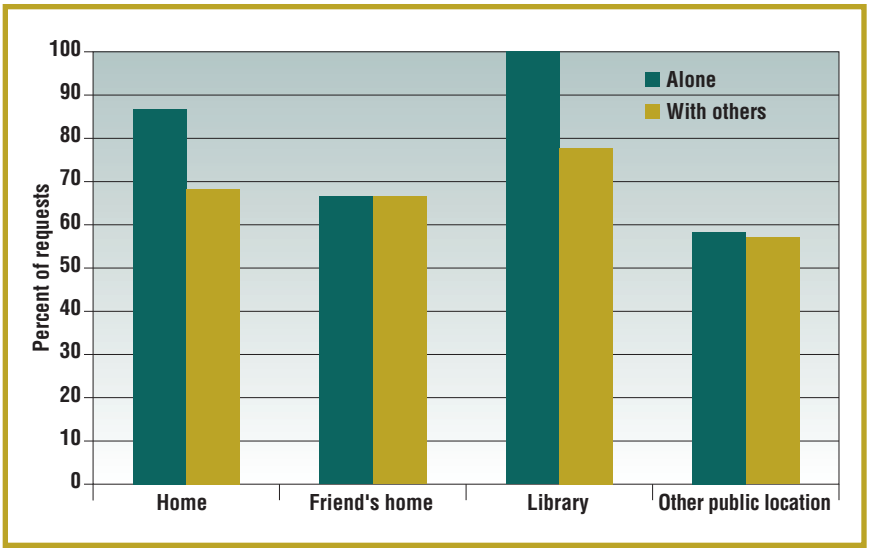

Figure 3. VP and CSWF users' willingness to share according to place and social context.

were at home. Indeed, they may have interpreted location requests as questions similar to "are you available to do something?" rather than simply "where are you?" In contrast, although participants were often willing to let others locate them when they were with friends, they seemed to indicate that they were content in the group they were with and not interested in having others find them.

We explored this issue further by analyzing VP users' willingness to share with different requester categories according to place depending on whether they were alone. Somewhat surprisingly, when VP users were alone at home, they were willing to share their location with anyone who asked for 25 percent of the requests, with email contacts for 39 percent of the requests, and with their list for 79 percent of the requests. When VP users were alone and not at home, including when they were exercising, in class, at work, eating in a restaurant, or in transit, they were the most willing to reveal location to people on their list (85 percent), followed by anyone who asked (59 percent), and then email contacts (37 percent). It is not clear why participants would be more willing to share with anyone who asked than with email contacts, no matter what the situation; however, there is no statistical difference between willingness to share with anyone and email contacts in this situation.

When VP users were with friends and not at home (typically engaged in a social activity such as at a sporting event), they were never willing to reveal location to just anyone who asked, but they were sometimes willing to reveal location to email contacts (about 25 percent of requests), and often willing to reveal location to people on their list (75 percent of requests). When VP users were with friends at home (for example, watching television or a DVD, playing video games, or studying), they were occasionally willing to reveal location to anyone who asked (6 percent), and somewhat more willing to reveal location to email contacts (29 percent) and their list (53 percent).

General privacy and security concerns

During the study, we also asked participants about their concerns regarding the privacy and security of email and instant messaging at each page in which they had participated in those types of communication in the previous 30 minutes. Here, we briefly describe how participants in our three revealed-privacy-policy categories rated their level of concern (on a 1 to 5 scale, where 1 = not concerned at all and 5 = very concerned) regarding the privacy of email and instant messaging, and how important they rated the security of these types of communication (rated on a similar 5-point scale).

Table 3 shows that CSWF users had significantly lower levels of concern about the privacy of email compared to both CP and VP users. VP users had the highest level of privacy concerns for both email and instant messaging, and these levels were significantly higher than for CSWF users. VP users also rated the importance of email and instant-messaging security higher than both CP and CSWF users. VP concerns might be related to their having the highest usage of both email and instant messaging.

Although privacy and security concerns about email and instant messaging are not exactly the same as concerns about location privacy and security, users' location policy preferences could be related to concerns about privacy in general, albeit not in a straightforward way. That is, those most willing to share location information with the most requester categories were also the most concerned about privacy and security of email and instant messaging. During the prestudy interview, we asked participants to rate their level of concern about the security of the wireless network they use. Surprisingly, given the differences we found in revealed privacy policies for location sharing, we found no differences in security concerns across the three privacy policy categories.

Participants in this study fell into three categories of sharing: those who never shared, those always willing to share with those on their list regardless of place, and those willing to share with different requester categories depending on place and social context. This suggests that for at least some users, privacy concerns vary across place and context, and therefore privacy policy controls need to be flexible enough so that users can satisfy their preferences. Such findings are consistent

TABLE 3

Consistent-private (CP), consistent-share-with-friends (CSWF), and variable-privacy (VP) users' revealed location-privacy policy for emails and instant messages (IMs), indicating privacy concern and security importance (both rated on a scale of 1 to 5, from lowest to highest), as well as usage 30 minutes before a page.

Revealed privacy policy	Email			Instant messaging		
	Privacy concern	Security importance	Mean no. of emails	Privacy concern	Security importance	Mean no. of IMs
CP	2.5	2.8	1.4	1.8	2.2	0.95
CSWF	1.8*	2.5	2.1	1.3	1.9	0.37
VP	2.95†	3.2‡	2.9§	2.5‡	3.2‡	1.85‡

* Mean is significantly less than other two categories, according to analysis of variance (ANOVA) post-hoc Sheffé test, $P < 0.05$.

† Mean is significantly greater than other two categories, according to ANOVA post-hoc Sheffé test, $P < 0.05$.

‡ Mean is significantly greater than CSWF category, according to ANOVA post-hoc Sheffé test, $P < 0.05$.

§ Mean is significantly greater than CP category, according to ANOVA post-hoc Sheffé test, $P < 0.05$.

with previous research findings that privacy preferences vary across activities,[13] situations,[10] and requesters.[10,11] Yet, we also found that many participants were highly consistent in their willingness to share location information, indicating that some users might be comfortable setting policy preferences once to govern all future use. The difference between consistent and variable-privacy categories identified in this study suggests that privacy may encompass both aspects of Leysia Palen and Paul Dourish's distinction between privacy as a dynamic social process and privacy as something dichotomous and statelike.[16] Given the limitations of our sample, as well as the complexity of these issues, we cannot draw firm conclusions. However, our findings suggest that further exploration of how and for whom privacy preferences are context dependent may be an important avenue of study.

Location-sensing technologies raise many exciting possibilities for the communication and delivery of services among users, devices, and places. These technologies also raise potential privacy and security conflicts if users don't understand how or what is being sensed or transmitted, or if they don't have adequate control over such information. Our study of users' revealed location-privacy policies indicates that developing pervasive computing environments that include location-sensing technologies requires understanding how preferences vary across place and social context for different user groups. For example, our study indicates that at least some users value simple privacy policies for their location-sensing applications and devices. Other users, however, might require more complex user interfaces for creating privacy policies that express a default policy with contingencies for special cases or that let users respond to individual requests and change preference settings in real time. The challenge in both cases is to develop interfaces that can adequately control information commensurate with user preferences but that do not constantly interrupt users.

Our study also has implications regarding the kinds of location-sensing applications that users might want to use. For example, users seem more open to applications connecting them to others when they are alone rather than when they are already engaged in activities with friends and others.

Further research is required to better understand location privacy behavior across a broader sample population. We also need to explore privacy behavior across a larger range of context-sharing technology. With a better understanding of these behaviors, we can design appropriate policy languages and user interfaces to encode privacy preferences in ways that will meet the expectations of users of context-aware technologies. P

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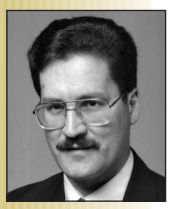

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