www.elsevier.com/locate/ijhcs

Biometric Data Sharing in the Wild: Investigating the Effects on Online Sports Spectators

Franco Curmi, Maria Angela Ferrario, Jon Whittle

PII: S1071-5819(17)30048-4
DOI: http://dx.doi.org/10.1016/j.ijhcs.2017.03.008
Reference: YIJHC2118

To appear in: *Journal of Human Computer Studies*

Received date: 17 October 2015
Revised date: 19 March 2017
Accepted date: 29 March 2017

Cite this article as: Franco Curmi, Maria Angela Ferrario and Jon Whittle Biometric Data Sharing in the Wild: Investigating the Effects on Online Sport Spectators, *Journal of Human Computer Studies* http://dx.doi.org/10.1016/j.ijhcs.2017.03.008

Biometric Data Sharing in the Wild: Investigating the Effects on Online Sports Spectators

Franco Curmi[a], Maria Angela Ferrario[b], Jon Whittle[b]

[a]*HighWire CDT, Lancaster University, Lancaster, LA1 4YD, U.K.*
[b]*School of Computing and Communications, Lancaster University, Lancaster, LA1 4WA, U.K.*

Abstract

There has been a market surge in both provision of and demand for fitness applications and sport wearables. These werables often come equipped with highly sophisticated biometric data (e.g. heart rate) functionalities that make the capture and sharing of such biometric data increasingly common practice. A few research studies have considered the effect that sharing biometric data has on those individuals sharing this data. However, little is known regarding the social impact of sharing this data in real-time and online. In this study, we investigate whether there is value in sharing heart rate data within social applications and whether sharing this data influences the behavior of those seeing this data.

We do so by conducting a study where the heart rate data of runners competing in a 5-km road race is shared in real-time with 140 online spectators. We collect rich quantitative data of user interaction though server logs, and a qualitative data set through interviews and online users' comments.

We then compare and contrast the behavior of online spectators who are presented with heart rate data together with contextual data, and those who are only presented with contextual data, for example, location. We also examine whether this difference is dependent on the social relation between the athletes and the spectators. Results indicate that spectators who are presented with the runners' heart rate data support the athletes more and rate the presented system more positively. These effects are dependent on the social tie between the athletes and spectators. This is one of the first studies to carry out an empirical investigation in the wild on the effects of sharing heart rate data in an online social context. In this light, in addition to supporting earlier literature, the outcomes present new insights and research directions within the sporting context.

Keywords: Heart Rate, Interface Design, Crowdsourcing, Human Behaviour, Research In The Wild, Sport, Spectators, Crowd Behaviour

1. Introduction

The use of biometric data such as heart rate data is becoming increasingly popular outside the medical practice. As the number of communication channels has increased throughout the digital era, so too has the diffusion of biometric data. Some socio-technical systems provide embedded features that allow users to share their biometric data. For example, freely available sports applications such as RunKeeper, Runtastic and Azumio, allow users to share their heart rate data over social networks in real-time. Similarly, a prevalence of fitness devices, such as the Apple Watch, Fitbit, and MI Band, capture and share heart rate data to social networks. Additionally, the decreasing price point and diversity of these applications is increasing the capacity for users to share this data (Chung et al. (2016)).

This data is also sporadically used in live public broadcasts. For example, the Red Bull Stratos event superimposed the heart rate data of an athlete over live video streams. This event was followed live by over 8 million online viewers (Caulfield (2012)). However, while this data type is increasing in use, its effect on viewers and the added value of broadcasting this data, if any, are still largely unclear. In other words, is it worth broadcasting this data? In this study, we are interested in understanding whether presenting athlete heart rates to remote spectators adds value and influences spectator behavior. Additionally, the work of Janssen et al. (2010) and Kurvinen et al. (2007) hints that the effect that heart rate data has on others might depend on the social relationship between the athlete whose data is being shared and those viewing that data. Thus, in this work we also investigate whether the influence on behavior when seeing another's heart rate is subjective, depending on the social tie.

We use the sport of running as this provides conditions for repeatability and research observation that fit our requirements. This affords a realistic context for a data sharing setting whose duration is neither too short (in which case the researcher does not have enough time to capture the necessary data) nor too long (in which case managing the setting may become too complex). Additionally, we have explored, in the last four years, how to design and develop systems that facilitate real-time remote crowd support during challenging sporting events such as marathon running, thus, this provided a familiar setting. By remote crowd support we intend that spectators who are not physically at the event can cheer the athletes remotely during the event. In this process, we iteratively developed and tested HeartLink (heartlink.co.uk), a system that allows athletes to broadcast location and biometric data to online spectators as the event unfolds. With HeartLink, online spectators can support their favorite athletes by clicking a 'Cheer' button while following their performance live. This creates a small vibration and a sound on the athlete's device (e.g. mobile phone), thus creating a physical connection between the athlete and the remote supporters. In this way, the athletes become aware that a crowd is following their performance. We are then able to utilize the cheering as one of the indicators for user engagement.

The outcomes of an earlier pilot study that considered the effect of cheering athletes, suggested that displaying the users' heart rates to remote others influences spectators' behavior (Curmi et al. (2013)). For example, spectators became anxious when the biometric data of athletes was interrupted during the sporting event. In this pilot study, we also identified that the use of heart-rate data during the sport broadcast presented logistical challenges that were not clearly justified by the increase in value for the spectators. These challenges included a limit in the number of heart-rate sensors that were available for the study at the lab where the investigation took place (N=8) and the increase in the complexity of the setup from the necessity of explaining-to and wiring-up participants. This scenario prompted us to empirically investigate whether the use of heart rate data justifies the expense of the additional hardware sensors and the effort of wiring participants. In other words, is sharing additional heart rate data in this context worth the trouble? It is in this light that we now further investigate the effect that the sharing of heart rate data has on those seeing this data in a sporting context.

Thus, through an in-the-wild study, we investigate the difference in behavior between those spectators seeing and not seeing heat rate data and why such a difference, if any, occurs. By recruiting two groups of spectators and randomly assigned each spectator either to a condition where the interface included the heart rate data of the athletes, or to a condition where the interface excluded the athletes' data, we compare and contrast behavioral difference between those presented with the heart rate and those who are not presented with the heart rate. Additionally, we investigate whether any difference is equally reflected among those who know the athletes and those who do not. The first group, recruited from the athletes' social networks, comprises the athletes' friends; we refer to this group as 'friendsourced' (Bernstein (2010)). The second group, recruited from a crowdsourcing platform and with no social connection to the athletes, we refer to as 'crowdsourced.'

In this light, this paper's contributions are as follows:

1. It reports on the online behavioral differences between spectators who are presented only with context data and spectators who are presented with both biometric and context data.
2. It reports on the online behavioral differences between friendsourced and crowdsourced spectators.
3. We then compare disparities between the four groups in conditions 1 and 2 above, the results of which indicate that the most engaged spectators are friendsourced spectators who are presented with the additional heart rate data.
4. Finally, we draw upon these results with support from the collected qualitative data from this study and its relation to the existing literature.

Section 1.1 reviews how technology-mediated heart rate data sharing evolved, from its emergence in the early 1900s up until the widespread diffusion through digital communication channels and seminal academic work in this area over a century later. We then describe the study's approach, methodology and emerging findings.

We reflect on the results from sharing biometric data in real-time through three theoretical concepts. 1) The sharing of personal informatics (Epstein et al. (2015)), 2) subjective versus objective information sharing (Bae et al. (2013)) and 3) boundary negotiated artifects (Lee (2007)). Boundary objects were first proposed by Star and Griesemer in 1989 to investigate the interaction of actors in a museum curating setting and the bridging of ideas across these actors. More recently, Lee et al. built upon this to differentiate between routine and non-routine collaborative work by injecting 'boundary negotiating artefacts' into the design discussion. It is the latter that we are most interested in for the non-routine use of heart rate sharing as a boundary object for the athletes, researchers and the spectators.

The next section reviews how technology-mediated heart rate data sharing evolved from its emergence in early 1900 up until the widespread diffusion through digital communication channels and seminal academic work in this

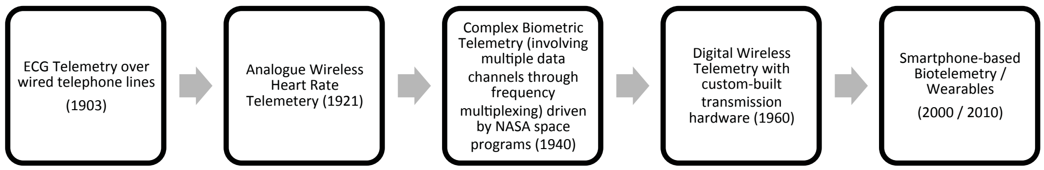


Figure 1: The evolution of biometric telemetry

area. We then describe the study approach, methodology and emerging findings.

1.1. The state of the art in heart rate sharing

Traditionally, medicine has been the driving force for advances in biometric data capture, processing and communication. The history of biometric data in health dates to the early 1900s, and the communication of biometric data, biotelemetry, was subject to rapid evolution through a series of disruptive technologies. Figure 1 highlights key milestones in this regard. These advances were initially driven by demands in health care (Grundy et al. (1977)); however, more recently, the rise of ubiquitous computing, particularly smart phone technology, facilitated a rapid dissemination of biotelemetry-based applications outside the medical domain.

The first reference to biotelemetry dates to 1903, when Nobel prize winner Willem Einthoven transmitted electrocardiogram signals from hospital to his laboratory over telephone lines (Nihal and Elif (2002)).The next change occurred 18 years later with the first transmission of heartbeats over radio. Subsequently semiconductors opened up multiple possibilities for biotelemetry as equipment became more stable, smaller and more accurate. Today, the availability of off-the-shelf biometric sensors and mobile devices lets individuals who are not necessarily medical savvy, to capture, log and share this data. Smartphone applications like RunKeeper, Runtastic and Azumio, among many others, are freely available and allow users to capture and share their heart rate data over social networks in real-time with great simplicity. For example, Azumio, reads the user's heart rate through a finger placed in front of the phone's camera without necessitating any additional sensors. More recently, Poh et al. (2010) developed a non-contact heart rate measurement application; through a webcam, they analyze minute changes in facial skin colors and determine the cardiac pulse.

In this scenario, while devices and applications that allow the sharing of heart rate data are on the increase, little is known regarding the effect this sharing has on those persons who remotely see this very personal data. While conducting a previous study in which the authors investigated the effect of the remote cheering on of athletes, the data suggested that relatives can become anxious when they perceive the heart rate of remote others as being high or when the heart rate is unavailable due to technical system failure (Curmi et al. (2013)). In this paper, we investigate this further, utilizing a setup within a sporting context specifically designed for this purpose. We consider whether the presentation of the heart rate data influences the behavior of those seeing the data, and analyze whether any change in behavior is dependent on the social relation between the data sharing user and the data viewer.

2. Biometric data sharing literature

Cases that involve biometric data sharing are quite common in recent human-computer interaction (HCI) literature (for example see Wang et al. (1992); Mueller et al. (2003); Konberg et al. (2003); Hallberg et al. (2004); Kurvinen et al. (2007); Schnädelbach et al. (2008); Perttula et al. (2010); Janssen et al. (2010); Slovák et al. (2012)). In our review, we look at studies across two clusters. We first highlight those that focus on augmenting the experience of spectators through data, such as the work of Konberg et al. (2003). The second group then clusters those that consider the effectiveness and social impact that sharing biometric data can have on participants. An example of the latter is the work of Schnädelbach et al. (2008) and Kurvinen et al. (2007). With this in mind, we will next look at the results that contribute to understanding the effect of biometric data sharing, first, as a representation of information, and second, as a way to influence social connectedness between individuals.

2.1. Augmenting the experience with data

Relevant work in this regard is that of a group of researchers at Lulea (Sweden), which presented two of the first known attempts in which biometric data was used to augment the experience of spectators (as reported in Armstrong (2007)). In their first project, the Arena project, Konberg et al. built a system that collects data regarding the breathing, heart rate and location of ice hockey players during a match. This data was shared with spectators via custom-made handheld devices (Armstrong (2007)). In Konberg et al.'s study, the work focused primarily on the communication technology that this one-way data sharing system utilized. In a second follow-up project at the same center, Hallberg and colleagues used similar custom-built technology to share data during the world's largest skiing event, the Vasaloppet week. Three skiers equipped with sensors took part in a 90-kilometer open-track non-competitive skiing marathon. The data collected included altitude, position, heart rate and speed. This data was connected through Bluetooth and GPRS technology to the context aware Alipes platform (Nord et al. (2002)) and was then presented to spectators who logged into the project's website through a Java applet (Hallberg et al. (2004)).

The outcome of these projects highlight the challenges faced when sharing data in real-time and 'in the wild' (Chamberlain et al. (2012)). For example, issues such as data loss were significant and amounted to 31% for the GPS data and 24% for the heart rate data across the ten-hour event. More importantly, the study reports that interruptions in heart rate data might have influenced the spectators' behavior during the event. This suggest a potential link between the presented data and the spectators' behavior, even though, no hard evidence emerged. The authors do, however, report that the technology seemed to enrich the viewers' experience and that this approach could be valuable in augmenting television sports broadcasts. Since then, the statistics presented through computer-generated graphics during television broadcasts, particularly in sports events, have increased considerably. Additionally, capturing biometric data and presenting this to the television viewers is now technically possible and relatively easy. However, the use of biometric data, such as heart rate, in public television and online broadcasts remains rare and sporadic. The reason for this remains largely unknown.

A series of projects further exploring this, were undertaken in Nottingham. *'The Experiment Live'* was an artistic event in which Paul Tennent et al. looked at the possibility of using biometric data during television broadcasts (Tennent et al. (2012)). Four participants were fitted with sensors and followed by cameras while they explored the basement of a presumed haunted house. The data was then broadcast live to a cinema where an audience followed the 40-minute event. Similar work at the same university was conducted by Schnädelbach et al. In this case, the researchers captured participants' data while on amusement rides. Data visualizations that contained live video, audio, heart rate and acceleration data, were presented to spectators in a nearby location (N=90) (Schnädelbach et al. (2008); Walker et al. (2007)). The study reports that the data broadcast 'extended the experience for riders while also enhanced the entertainment value for spectators' (Walker et al. (2007) p.121). Walker et al.'s results do not single out individual data types from the presented visuals and the effect these types had; this is an aspect we are interested in investigating.

Worth noting is that the above-mentioned cases present a direct mode of communicating the heart rate data. Data viewers are presented with the value of the data in a predominantly screen based interface. Other studies, such as the work of Schnadelbach et al. (2012) and Snyder et al. (2015), shared data through an indirect modality. Snyder et al. developed an interactive ambient lighting system, Moodlight, that changes the emitted color based on the level of arousal of participants. With this prototype, they explored the effect of biosensor data on personal and social implications. Closely related is the work of Schnädelbach et al. in which a prototype building, ExoBuilding, visually and physically adapts to the users' physiology. By taking inferences from the user's heart rate, respiration and skin response, the prototype building changes color, acoustics and shape (for example it expands).

2.2. Effect on social connectedness

In 2007 Kurvinen investigated the effect of sharing the biometric data of a football team with their families and coaches (Soleymani et al. (2012); Kurvinen et al. (2007)). In this study, football players wore heart rate sensors, and the heart rate data of each player was transmitted in real-time. This data could then be openly seen from mobile devices that were located around the pitch. They found that sharing heart rate data added an element of competition between the parents, who expected their children to be the most fit in the group. They report that sharing the individual's heart rate motivated the parents to encourage the athletes to attend sports practice more frequently with the aim of increasing fitness. The discussions also highlighted the general lack of understanding of the heart rate data in the study population. Despite this, the data sharing still became a tool for generating social interaction, as parents discussed and joked about the presented data during the games. The authors claimed that this interaction would not have happened without the data sharing component.

A similar investigation over a longer period and with differing conclusions was conducted by Slovák et al. (2012). Slovák et al. studied the effect of exchanging heart rate data in real-time between five couples over a two-week period. In this case, the authors highlighted the necessity of having contextual information to correctly frame the heart rate data. They report that viewing the heart rate data without any additional context was not very meaningful for the remote data viewers. For example, by seeing remotely that your partner's current heart rate is 120, leaves room for multiple assumptions, for example, the person is running or stressed or excited. This emphasized the importance of context awareness that gives meaning to heart rate values. On the other hand, the 'mystery' of not knowing the precise context may help to create an increase in the 'feeling of connectedness' that Slovák et al. reported between the participants. This contrasts with earlier referenced studies involving specific sports contexts with shorter time frames. In this case, the participant-pairs, who were intimate couples, reported feeling an increase in emotional connectedness with the remote other when knowing that the data visualized represented a physical aspect of the other person. This again suggests, that sharing heart rate data generates different feelings to different individuals. This difference seems related to the relationship between the participants, prior to sharing the data. Participants remarked that sharing the heart rate data represents great openness, as, unlike facial expression, it is something that you cannot intentionally control. This is even more pertinent when this data is shared in real-time (Slovák et al. (2012)).

The increase in social connectedness is also supported in the work of Janssen et al. (2010). In a lab-based experiment, Janssen and colleagues presented participants with the sounds of real heartbeats from a known person, those of an unknown person and computer generated heartbeat sounds. Participants associated an increase in heart rate with an increase in emotional intensity (Janssen et al. (2010)). However, when listening to the heartbeats of unknown persons, the participants did not feel any increase in connectedness. They did feel an increase in social connectedness when the heartbeats they listened to were of a known participant, thus indicating that the degree of connectedness between the participants affected how much influence heart rate data sharing creates and the state of the social relation between the participants before the experiment. These results are confirmed by O'Brien and Mueller in 'Jogging over a distance' (O'Brien and Mueller (2007); Mueller et al. (2010)). O'Brien and Mueller developed and tested a context-aware system that shares ambient sound and heart rate data between two remotely located joggers. Each jogger was equipped with a heart rate sensor, a pair of headphones and a telemetry device. The telemetry device transmitted ambient sound and heart rate to the remote device and vice versa. The jogger with the highest exertion effort (as deduced from the heart rate) heard the other jogger as if he or she was behind. Again, the results, in this case, indicated that sharing heart rate data in real-time facilitated the social experience of the participants. The use of heart rate as an indication of effort provided a means for athletes to interact and compare their performance in real-time.

In summary, the above work suggests two key influencing factors in heart rate sharing, namely: 1) the context in which the data is shared, and 2) the social relation between the person sharing the data and the data viewer. We investigate the latter empirically in a real-time data sharing context between a group of co-located athletes and distributed remote crowds.

3. Procedure

The work presented here is part of a larger study that considers facilitating remote crowd support in real-time contexts. This work is composed of a number of iterative in-the-wild studies. The first study comprised a pilot study conducted during a triathlon, with three athletes and nine online spectators (Curmi et al. (2013)). With the insights collected from this work, HeartLink, a system for sharing data in the wild was designed and built (Curmi et al. (2014)). We use HeartLink to broadcast data in real-time from the athletes to different spectator groups that are located remotely and observe spectator behavior.

(a) Event environment (b) Positioning devices on participants

Figure 2: Event pictures

Figure 3: HeartLink research application was running on athletes' devices and broadcast telemetry data to distributed spectators.

3.1. System Design

In this study, five athletes from a university club were invited to take part in a 5-km race (Figure 2). In return, a donation was given to the club after the event. These athletes were willing to participate in the event and ready to share personal data using HeartLink. The athletes were each given a heart rate sensor, an armband and a smartphone device (Nexus 5), which was running the HeartLink mobile app (Figure 3). HeartLink was configured as shown in Figure 4. The app connected to a Polar WearLink heart rate sensor via Bluetooth, computed the user's geographical location and broadcast this data to a remote server via a mobile network. The data broadcast included heart rate, latitude, longitude, altitude, bearing, data accuracy and the time of the last reliable data update (GPS Fix). Prior to agreeing to participate in the study, the athletes first attended a briefing meeting, which lasted one hour. In this meeting, the athletes were informed about the scope of the study, how the system works and how the subsequent stages of the study would unfold.

The information shared with the athletes included logistical information, such as the time of the event, safety information and the racecourse. The athletes were then given an appointment at the race location thirty minutes before race start. To ensure consistency, all devices were reconfigured and positioned by the researchers who were coordinating the co-located athletes. Immediately after the race, the athletes, together with the race organizer of the same running club, participated in a focus group that collected insights on the experience of the athletes when sharing data and being cheered on during the event.

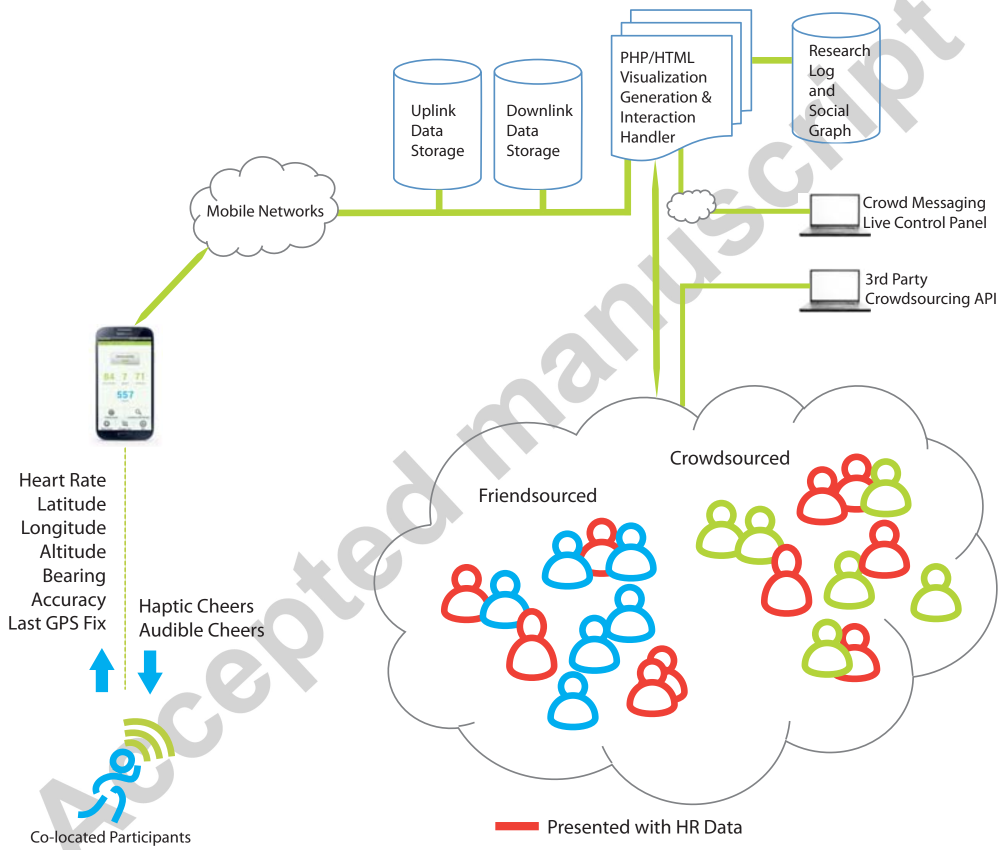


Figure 4: The system infrastructure.

As earlier stated, the data was broadcast from the athletes to a remote server via mobile networks. The server receiving the data then generated and presented visuals to online spectators via their web browsers. These visuals were based on HTML, PHP scripts and CSS style sheets with communication over a specifically built RESTful API. Figure 5 shows a sample spectator interface. All the data was dynamically updated at 2-second intervals, thus giving a 'real-time' feel.

Some 140 spectators were recruited for this event. These were composed of two groups. 64 participants were recruited from the athletes' social networks. We recruited these participants through communication on the athletes' Facebook channels and through their departments' mailing lists. Thus, these spectators knew the participants. In addition, 76 participants were recruited from CrowdFlower, a crowdsourcing platform that at the time of conducting the study accepted European requesters. This approach minimized the probability of having participants within this group that were socially connected to the athletes. All spectators were English speaking and distributed across the globe, with a predominance of participants within the UK. Spectators followed the event from 32 different countries and had a mean age of 26.3 years. Figure 6 shows the geographical distribution of the spectators.

The spectators were first presented with an overview of the study and were asked to log in to the main event web page through a custom-built Facebook app. After this, they were introduced to the interface and briefed on how the system works, the function of the cheer button and the effect of submitting posts. On the main interface, they could select the athlete that they were interested in following. For the selected athlete, they could see live data and send live 'cheers' to that athlete by clicking a Cheer button. The spectators could change which athlete they wanted to follow at any time. The Cheer button generates a small vibration on the device that is carried by the athlete and makes the athlete's device call out the name of the person who sent the cheer. This makes the athlete aware that a crowd is following their performance. Thus, the live cheering feature has two functions. It creates an immediate feedback channel from the spectators to the athletes. Additionally, it provided an important measurement point for comparing and contrasting spectator behavior in a real-time setting.

At login, each spectator was randomly assigned to one of the two conditions (Figure 7). Participants in the control condition were presented with live data consisting of the distance covered by the athlete, the percentage of the race that was completed, speed, pace and a map with an overlay of the athlete's completed path. This was intended to give the spectators an understanding of how the performance was unfolding. The experimental group was presented with the same data plus the athlete's heart rate, the average heart rate and a chart displaying the heart rate data. During the event, all specta-

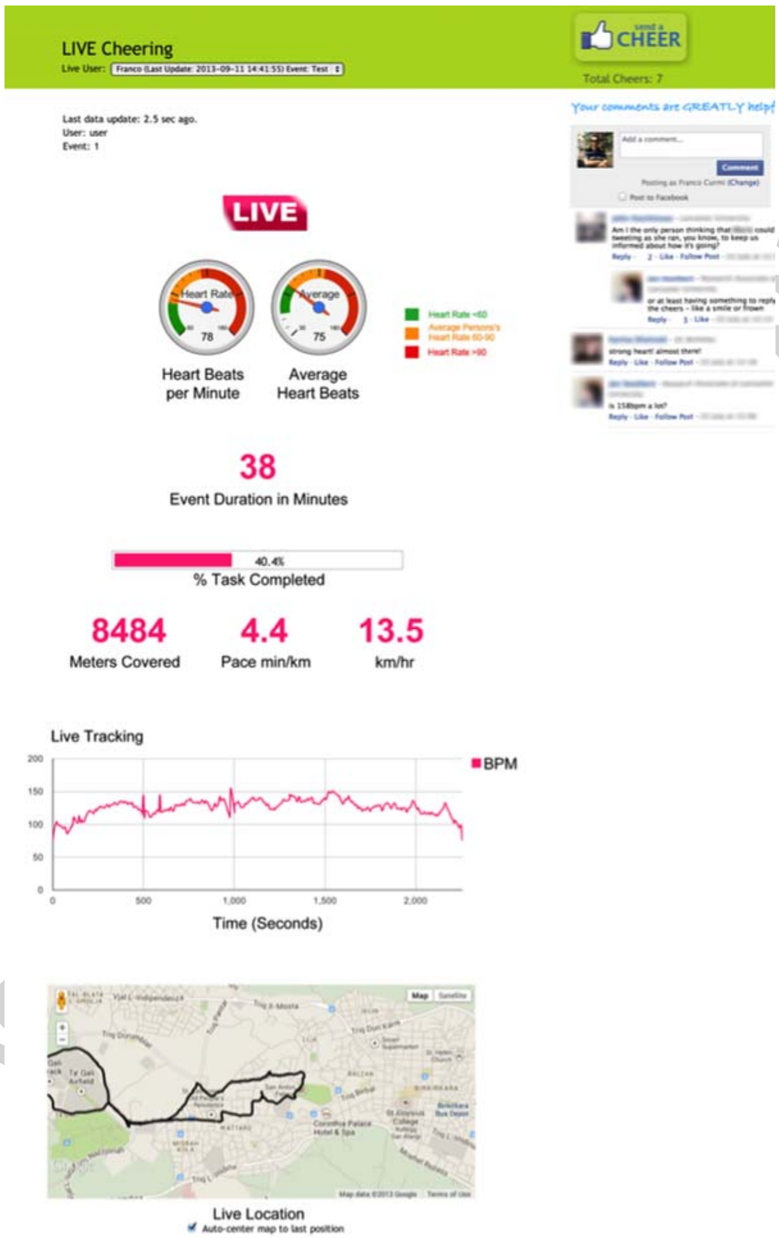


Figure 5: Sample spectator interface

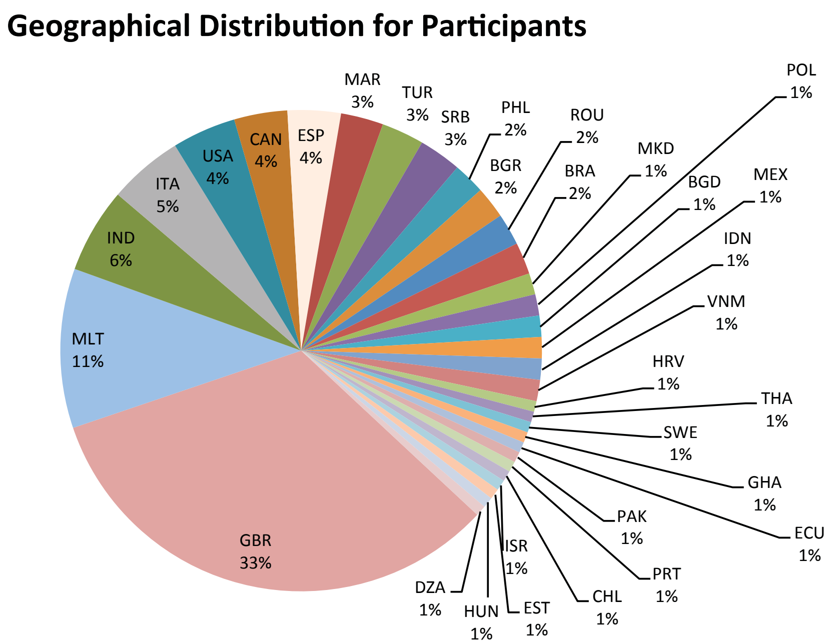


Figure 6: Geographic distribution of spectators who followed the live event with percentage for each country code.

Figure 7: Spectator login sequence.

tors could also send posts through a Facebook frame within the interface, as shown in Figure 5. To ensure that there was no cross contamination in the data between the control and experimental groups, each spectator only saw the posts that were sent by those who were following the same athlete and within the same experiment condition. By default, the posts sent were only visible on the HeartLink website and were not posted to the participants' Facebook profiles.

After the event, spectators were interviewed through a survey that collected data on the experience of the different spectator groups, how likely they were to recommend the system, and their view of the presented information, amongst others. For a detailed account on system design and infrastructure, the readers are encouraged to see Curmi et al. (2014). In the next sections, we report on behavior differences between spectators, particularly, those who were presented with live heart rate data and those who were not presented with this data.

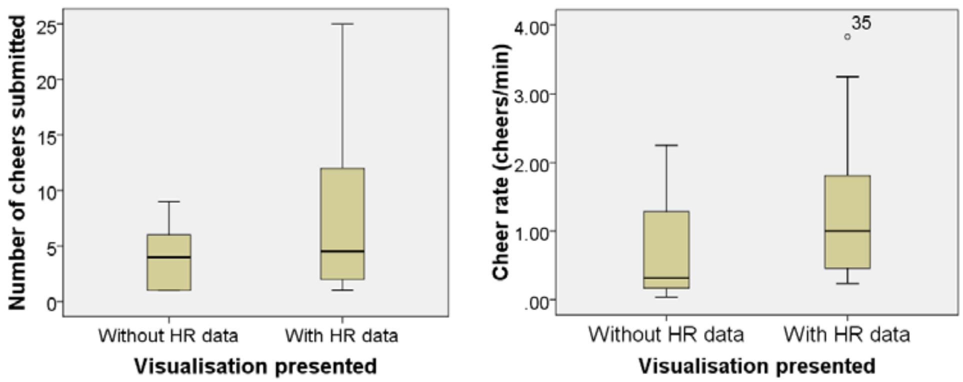
4. Results

The findings that are reported in this section are derived by comparing and contrasting the time that participants spent on the site, the number of cheers that different participant groups submitted, and the cheering rate (cheers submitted per minute). This information was collected through server logs for a total of 6,853 data points. Additionally, we substantiate these finding by reporting on behavior differences in participant groups based on the messages posted during the event and the results of the post-event survey. As is common practice in studies that involve unknown crowdsourced participants (Mitra et al. (2015)), we filtered out spammers (for example participants who enter random text in the post event survey) from the crowdsourced spectator group. Additionally, during the event there were three instances in which the data that was transmitted from an athlete to the server was interrupted due to momentary loss in the mobile data network connection along the course. To ensure data consistency and validity, after the event we went through the data set, identified spectator-participants who experienced such data loss and excluded their data in the reporting. This resulted in a valid population of 41 spectators.

In summary, we find that spectators who are presented with additional heart rate information show an increase in engagement in terms of the total number of cheers submitted as well as the self-reported ratings for the presented system. At the same time, there was no significant difference between the spectator groups in the time they spent supporting the athletes.

4.1. Cheers, Duration on site and Cheer Rate

The results show a significant difference in the total cheers submitted by those spectators that were presented with the heart rate data (M=15.83, SD=28.48) as compared to those who were not presented with any heart rate data (M=3.93, SD=2.96); t(23.8)=2.029, p=0.05 (Figure 8a). Conversely, we



(a) Cheers submitted grouped by the type of data presented

(b) Rate of cheers submitted by spectators for each spectator group

Figure 8: Figures contrasting differences between the behavior of spectators with additional heart rate data and without additional heart rate data

encounter no significant difference in the time spent on the site by those spectators who were presented with the heart rate data (M=16.38, SD=20.73) as compared to those spectators who were not presented with the heart rate data (M=21.44, SD=25.91); t(27)=6.58, p=0.52. The results also show that the cheer rate during the event (cheers per minute) of the spectators who were presented with the heart rate data is more than twice that of the spectators who were not presented with this data. However, a t-test did not determine this result as statistically significant; t(36)=-2.02, p=0.19 (Figure 8b).

The matrix scatter plot in Figure 9 takes a deeper look into this by presenting the cheers and duration across source groups and data conditions. We find a significant difference in the scores for cheers submitted by the friendsourced participants (M=19.26, SD=31.2) than the crowdsourced participants (M=3.65, SD=3.1); t(37)=2.23, p=0.03. There is also a significant difference in the time friendsourced spectators (M=29.1, SD=28.1) and crowdsourced spectators (M=8.12, SD=7.49) spent on the site; t(39)=3.3, p=0.02. However, the rate of cheers (cheers/min) did not reach the conventional statistically significant difference between these two groups; Friendsourced group (M=2.64, SD=5.07), crowdsourced (M=0.65, SD=0.58); t(38)=1.74, p=0.09.

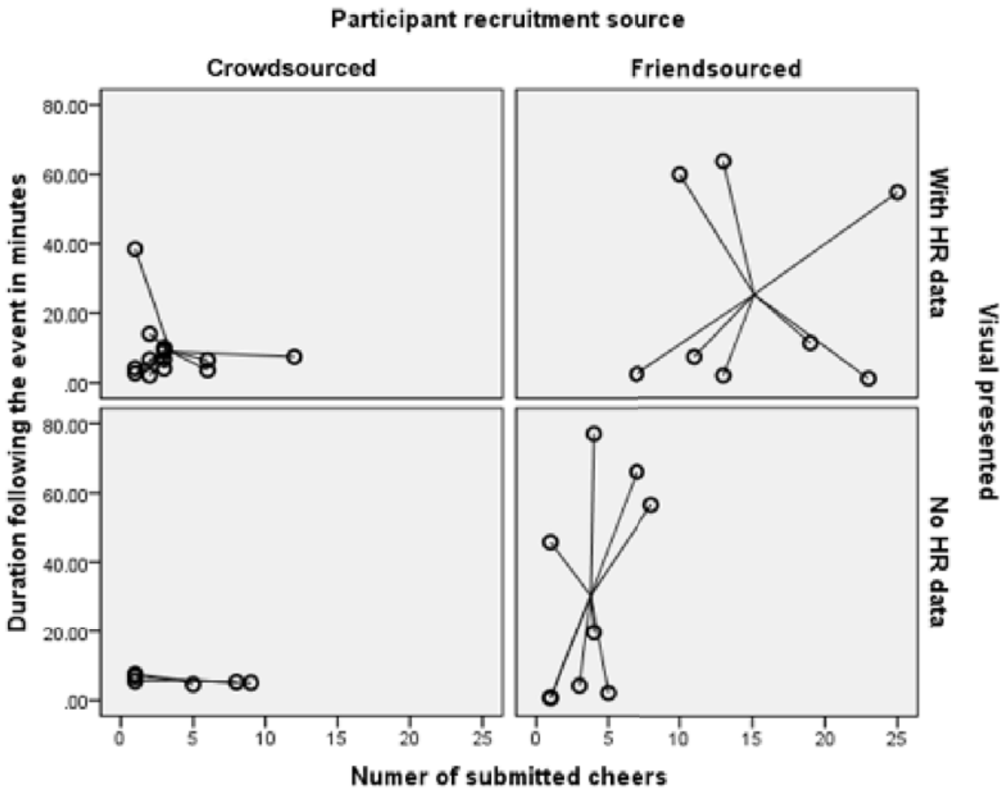


Figure 9: Scatter matrix plot with centroids of spectators' duration on site by cheers submitted for spectator recruitment source and data presented.

4.2. Social network posts

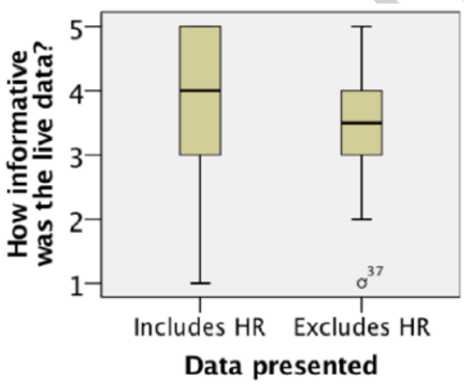
Table 1 shows the number of posts that the spectators posted on the interface. Across all athletes, the spectators who were presented with additional heart rate data submitted more posts (N=28) than those who were not shown any heart rate information (N=7). The participants observing the heart rate data were more engaged with the athletes, based on the number of comments posted.

4.3. Post event survey

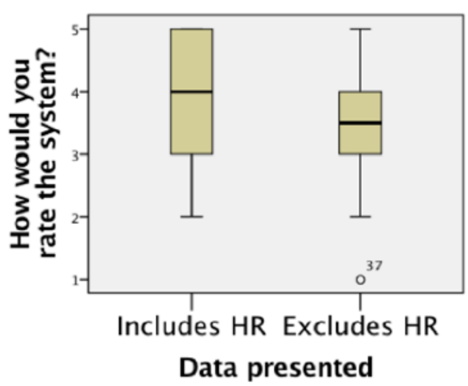
Immediately after the event was completed, the spectators were presented with a survey that collected feedback on the system. Questions asked in the survey were intended to understand the respondents' readiness to use the

Athlete number	Post from spectators seeing heart rate data *N* (%)	Post from spectators not seeing heart rate data *N* (%)	Total *N* (%)
1	5 (14.29%)	0 (0.00%)	5 (14.29%)
2	7 (20.00%)	2 (5.71%)	9 (25.71%)
3	2 (5.71%)	0 (0.00%)	2 (5.71%)
4	3 (8.57%)	1 (2.86%)	4 (11.43%)
5	11 (31.43%)	4 (11.43%)	15 (42.86%)
Total	28 (80.00%)	7 (20.00%)	35 (100.00%)
Comments on landing page (not attached to a specific athlete)			28
Total comments submitted			63

Table 1: Social network posts submitted by spectators



(a) How informative was the live data (from 'Not Informative - 1' to 'Very Informative - 5' on a 5 point scale)?



(b) How would you rate the system (from 'Bad - 1' to 'Good - 5' on a 5 point scale)?

Figure 10: Participant responses right after the event

presented system, the respondents' understanding of the live data, to gather insights for subsequent system design iterations and to identify any possible spammers among the respondents (e.g. users responding to compulsory questions with random text).

The results from the survey support the quantitative findings. Figure 10 shows the mean responses by the different spectator groups for two key questions, namely, 'How informative was the live data?' and 'How would you rate the system?' Comparing the responses of the two groups in the first question with an independent sample's t-test indicates that spectators that were presented with heart rate data (M=4.03, SD=1.03), report finding the interface more informative (M=3.5, SD=1.11); $t(66)=2.03$, $p=0.05$. Those presented with the heart rate were also more positive when asked to rate the system (M=4.08, SD=1.05) in contrast with the control group (M=3.50, SD=1.11); $t(66)=2.22$, $p=0.03$.

Spectators who were presented with additional heart rate data	**Spectators who were not presented with additional heart rate data**
It would be nice to have albums of athletes to help picture the person [P3]	The design of the page could use some work [P78]
Be more personal, less anonymous [P5]	Improve the streaming [P93]
You can add more features like distance between athletes [P20]	Definitely needs more exciting features [P89]
I'd like to watch them too [P24]	Better page layout with more information [P94]
Maybe a graphic of an athlete running and his/her resistance on the track, I would like to see his/her heart beat rates on different checkpoints on the track [P28]	There should be more colour and images. Make it more interactive and understandable [P68]
I never heard about an app like this. I think is something new and interesting. Perhaps in lonely sports (running, cycling...) athletes need a psychological support (people support) that team sports don't need. You need to feel that you are not alone, there are a lot of people behind you [P28]	Nothing in particular, it's rather simple and clear [P126]
It needs to be more personal [P12]	I think the layout could be improved [P97]

Table 2: Selected spectators' responses when asked to suggest improvements

This finding is also supported by the qualitative data that was collected after the event. The spectators' comments were coded and clustered in

Spectators who were presented with additional heart rate data	**Spectators who were not presented with additional heart rate data**
It is great that we can see the heart rate of runner in different distances [P24]; The heart rate [P17, P20, P25, P26, P39]	Despite this being a novelty I would expect more stats. I use Endomondo for my workouts and it appears to have more information, even if it is practically useless like estimated water consumption, burned calories, fastest km etc. [P97]
I did not need a map to know where the runner is as I am concentrated more on the details of the organism [physiology] of the player [P23]	No comparison to his/her stats, would like to compare the current run to other regular runs, how is he/she doing at the moment [P135]
I like the adrenaline to be supporting athletes [P34]	The app is real time [P106]
I like that it is live so you get accuracy [P3]	The ability to follow the run and cheer the athlete. [P80]
We can do anything on this world even when we are not close to them!!! [P15]	Without a doubt the live follow button. Watching (sort of) people actually do something is more meaningful than post race stats [P79]

Table 3: Selected spectators' responses when asked to identify what they liked most

themes (Campbell and Schram (1995)) that were generated from the data itself (Kissling (1996)). It is worth noting that the 19.35% of respondents who were not presented with the additional heart rate data recalled the cheering as the most interesting feature. In contrast, the 13.5% of spectators who were shown the additional heart rate data recalled the heart rate visuals as the most interesting feature, and only one respondent in this group recalled the cheering element. This suggests that the real-time heart rate superseded the interest of the cheering feature.

We notice that these differences are also reflected in the spectators' interview responses collected after the event. For example, the responses of the spectators who were presented with the additional heart rate data can be more easily associated with an empathetic theme than the responses of the other group. They were also more likely to be human centered rather than systems centered, as can be seen in Table 2 and Table 3, which show selected quotes from spectators' responses when asked for suggestions for improvement and identification of the most liked features respectively. We will later get back to this in the discussion section.

Finally, to give the reader a sense of the context in which the activity was taking place, below is an extract from the participants' discussion at race completion.

> Discussion between researchers (R) and athletes (A) at end of race
> R1: *yours is 137 cheers.*
> A2: *137 cheers? all for one person! 137?* (excitement /laughing) *quite a lot.*
> A2: {some time later; asking A1} {Is that the most cheers?}
> A1: *what's the cheer count you've got?...*
> {later} Co-located spectator: *how much have you got?*
> A2: *a 137 cheers apparently*
> Non participating athlete: *you're a popular man*
> A2: *137? that can't be right; a 137 in all? in total?*
> R1: *no no, just for you*
> A2: *just for me? What!*
> Race Organizer {teasingly}: *oh we're getting insane there. I don't know who said I don't want my arm to be cheered (before the race).*

This discussion highlights the athletes' excitement from receiving the cheers. The numbers of cheers received become the key element of discussion among the athletes upon race completion. More importantly these comments show that for the participating athletes the cheers received were not stochastic but were motivated by their own performance, popularity and the data they shared. We will also further elaborate on this in the discussion section. In summary, the results indicate that in the conditions described, the live heart rate of athletes affects remote spectators differently. Specifically, the cheers submitted suggest that online spectators of sports events show more engagement when presented with additional live heart rate data of the participating athletes. However, we did not find any significant increase in the time spent on the site between the two groups.

5. Discussion

This study provides some interesting discoveries. The results indicate that spectators who are presented with the heart rate data of remote athletes are likely to be more positive about the system and to cheer the athletes more. Our observations during the event suggest that the heart rate visuals shift participant attention to the effort exerted by the athletes.

5.1. Reflections on design implications

Both the design process and the results bring up a number of interesting questions relating to the study. Key questions within the design process include: How should we present the data and how detailed should this be? How can we minimize the disruption on the athletes such that sharing data, particularly biometric data, is seamless? How could this interaction be scaled up to larger events? Is it worth sharing this data and wiring up participants for the added physiological data sharing features? Would this affect the spectators' engagement in any way? And most importantly, what can we learn for future designs? The next sections focus on the latter through developing the findings along four main themes.

A: Biometric data visualisation improves the understanding of athlete's effort. The spectators' mental interpretation of the heart rate is dependent on both their individual tacit knowledge and explicit knowledge (Polanyi (2009)). To varying degrees, spectators interpret the live heart rate visuals through their a priori knowledge of, for example, what a value of 165 beats per minute represents. Should the spectator have explicit knowledge from past experience, then this knowledge is likely to be applied in this context by relating it to the presented value. On the other hand, those lacking any experience of heart rate data interpretation may be put off by its representation or might build a mental interpretation of the situation based on the context rather than the data per se. For example, by presenting the heart rate data in a dial graph where 150 beats per minute is represented in a red segment, then the visual may convey high exertion, not necessarily because of the data per se but because of the context. That is, the needle at the end of the dial scale is associated with a high value and this is reinforced with the red legend, where red is typically associated with 'alerts' (Qingbin (2009)). This would then contribute to the spectators' a priori experience for (future) post-priori cognition.

B: Spectators seeing the heart rate become more context-aware. Information can be subjective or objective. Subjective information can be perceived in an interpretive manner, while objective information is not subject to interpretation (Bae et al. (2013)). For example, data captured from sensors, such as the geographical positioning of the participant on the map, is considered as objective information and leaves little room for ambiguity or self-interpretation about the participant's position as long as we assume that the data is accurate. However, different viewers can interpret subjective data, such as a post on Facebook that says 'I'm struggling' differently and this can be very much influenced by the context. Knowing that the context of this post is that of a student studying at home, gives a completely different meaning than knowing that the person is a patient. The context influences how the participants interpret their environment (McCarthy (1993)). The objective information, such as the data that is collected from mobile phone sensors, has a low level of expression of contextual information (in comparison to for example a descriptive narrative of the context). However, context contributes a significant impact to the cognitive understanding of a situation (Bae et al. (2013)). A change in context can transform the interpretation that the user makes of the 'mental representation of reality, even when reality has not changed' (Bolchini et al. (2009) p.136.)

Bae et al. (2013) show that both subjective and objective context information can influence what other users understand of the context. This, in turn affects their social supportive behaviors. Different studies use different types of context information. Bae et al. (2013)) use four context types - activity, emotion, location and physical environment. Dey (1998) uses emotional, location, orientation, time and day information. Our work uses activity, location, time, day and physiological state. We observe that although all the data is presented in an objective form using numbers that were generated through sensors, the heart rate still provides a strong element of speculation and self-interpretation. In other words, although all the spectators are concurrently seeing the same data and know the same context, individually, their understanding of what 160 beats per minute represent differs.

Additionally, over time, this process helps spectators learn what heart rate values represent. First, seeing the heart rate of others helps in building a personal 'historical average' of what a typical heart rate in this context may be. This historic context, in combination with expectations management, may explain the spectators' reactions. For example, should spectators repetitively see the heart rate of participants at around 120 beats per minute within successive similar events, then their expectations of the data are adjusted accordingly. Should then the spectators be presented with a heart rate of 175, they are more likely to interpret this as the athlete exerting extreme effort.

C: The heart rate bridges the spectators' understanding of the athletes' experience during the race as a boundary object between the athletes, the spectators and the event organizers. From the literature discussed earlier, we derive that the heart rate as a negotiated boundary object fits in the compilation category. Through the sharing of the biometric data captured from the sensors, we attempt to bring the understanding of the spectators' community closer to that of the athletes. This data presents a relatively rare case of compilation boundary negotiated artefacts for two main reasons. First, the data is automated and is not explicitly and intentionally constructed by an actor within the communities. Second, the discussion that is generated around the object takes a different communication channel than that received by the object, i.e. through cheering. This process creates elements of ambiguity with the different stakeholder communities, who may be using and interpreting the heart rate differently. These elements of ambiguity are similarly found in the work of (Slovák et al. (2012)) and (Kurvinen et al. (2007). It would be interesting to go beyond ascertaining a relationship between the heart rate as a negotiated boundary artefact and social ties, to achieve a deeper understanding of what participant groups think the presented biometric data represents and how this contrasts with what it actually represents. This can be examined though common ethnographic methods such as in-depth interviews. A more complex, and possibly more interesting investigation, could consider how the negotiated artefact within the entire real-time ecosystem is interpreted by the different stakeholders and how this influences the evolving trajectory of the same artefact. For example, an athlete may associate the received feedback (cheering) to a variation of his or her exertion and this may influence the same exertion. Evidence of the influence of cheering on the athlete is found in the athletes' statements at the post event focus group that were presented at the end of Section 4.

The increase in emotional themes that can be derived from comments posed by those who were seeing the heart rate data suggests that viewing the heart rate makes spectators feel closer to each other. This observation was also indicated by Janssen et al. (2010), where heart rate data was shared between couples during day-to-day activities. The observed increase in engagement from the spectators who were presented with the heart rate in our study suggests that we can extend this observation to crowds. Spectators who were presented with the heart rate data provided comments that could be more easily attributed to empathetic themes, for example, using nouns and focusing their comments on 'athlete,' 'person,' 'effort,' 'loneliness' and 'psychological support,' in contrast with those who were not presented with this additional data. The latter focused their post-event comments primarily on the technology, using nouns such as 'the system,' 'the streaming,' 'features' and 'the layout' (as shown in Table 2 and 3 earlier). Further research in this area should investigate whether this effect is consistent across different groups and conditions.

D: Finally, real-time automated biometric data broadcast may be perceived as more reliable than manually inputted curated data. P3 comments 'I like that it is live so you get accuracy.' This and similar comments (e.g. P23 in Table 3) highlight the underlying assumption that real-time data is more truthful because it is seemingly impossible to curate. Additionally, heart rate data is widely considered as very personal data due to its ability to communicate feelings and emotions. This is particularly highlighted in Slovk's work, where participants who shared their heart rate while playing poker were concerned that would expose their strategies (Slovák et al. (2012)). Prior research showed that humans appreciate those who share personal information, and the sharing of such information creates greater intimacy among individuals Worthy et al. (1969). Self-disclosure can vary in breadth (variety of shared information), length (longitudinal time) and depth of information (Miller et al. (1983)). In this study, the significant increase in engagement that those who were presented with the heart rate data showed and the more empathetic comments that this groups submitted suggests that the heart rate data sharing contributes to an increase in the 'depth' dimension of self-disclosure. This merits further investigation.

5.2. Limitations and future work

The time is ripe to develop a theoretical model for the sharing of personal informatics, particularly, when this happens in real-time. A relevant model in this regard is Li et al.'s stage-based model of personal informatics systems (Li et al. (2010)). However, this widely cited and commendable model focuses on the flow of personal data and stops short of framing the sharing of personal information. Our work highlights a need of a new theoretical framework around sharing personal informatics in this context. This is worth exploring within the HCI and CSCW (computer-supported cooperative work) communities as increasingly social networks are nudging users to share events in real-time. In the light that the data sharing component of personal informatics is on the increase (Epstein et al. (2015)), an extended model that takes into consideration the data sharing of personal informatics in a real-time context is pertinent. While such a model could take many forms and directions, we envisage that this should include novel approaches of sharing personal informatics between individuals, crowds, and the combination in between. Such a model should differentiate between real-time and offline sharing across a spectrum of slightly personal to extremely personal data. This is expected to bring together the theoretical constructs that were referenced in this paper, among which, boundary negotiating artefacts (Lee (2007)), subjective versus objective information sharing (Bae et al. (2013)) and the sharing of personal informatics Epstein et al. (2015)).

The results indicate that sharing heart rate data can have a positive effect on spectator engagement. We are unable to pinpoint one specific reason for this. The spectators' behavior seems dependent not only on the crowd itself but also on the individual personalities and situational factors, as discussed earlier. Our analysis does not consider the values that were presented to the spectators (e.g. a heart rate of 170 vs. 120). We expect that future work will further refine the insights in this direction. Research in psychology and social media shows that individuals are more reactive to negative information than positive information (Daignault et al. (2013)) as rationalised through the negativity bias (Baumeister et al. (2001)). In this light, we expect that if viewers are aware that a higher heart rate value represents greater exertion, spectators are more likely to engage with the interface and provide support in ways that they believe is most supportive. Future work should examine these assumptions, for example by conducting a multivariate analysis on variations in data-representation and types, such as the current athlete's altitude, the course's gradient, or the athlete's position in the race. However, researchers embarking on such a feat might have to reconsider using an in-the-wild methodology, as trying to control many external variables in an in-the-wild methodology is extremely challenging, if at all possible (Rogers (2011)).

These results are congruent with existing research on heart rate data sharing in other contexts. Janssen et al. showed that heart beat communication can be considered by others as an intimate cue (Janssen et al. (2010)) while Slovák et al. indicated that heart rate communication can improve social connections (Slovák et al. (2012)). The increase in spectator engagement reported in this paper could be particularly relevant, not only for online social networks, but also for traditional one-to-many broadcasts. Understandably, more research is needed to generalize these results.

Presenting additional heart rate data during the televised broadcast of sport events promises an increase in viewer engagement. This is most relevant for sports broadcasts where athletes' performance is based on exertion (Hallberg et al. (2004)). For example, presenting the average heart rate of two teams playing in a televised soccer match could enhance the story being conveyed by the broadcast, while giving commentators greater opportunity for discussion and making televised graphics more dynamic. In recent years, television broadcast has increased the quantity of graphical information and statistics presented to viewers, while studies show that dynamic graphics positively affect viewer engagement (Galily (2014)). Additionally, heart rate data may enhance story telling because of the added detail that constructs the context. For example, presenting the average heart rate of two competing teams can help the spectators to better hypothesize which team is most tired and thus less likely to improve performance.

While technically achievable, these implementations pose social challenges, particularly due to the sensitivity of biometric data, ethical issues and diverse legislation on the topic. Although these are very important issues that need to be factored in, in this paper we focused our attention on the impact that sharing heart rate data can have on remote online spectators.

6. Conclusion

We compared the effects of sharing heart rate data on user engagement in a real-time feedback context. To the best of our knowledge, this is the first empirical work that investigates whether the presentation of heart rate data, in a CSCW sporting context, influences spectator behavior. We recruited online spectators who followed athletes during a 5k-road race. Each of the spectators was randomly assigned to one of two conditions; in the control condition the spectators were presented with live locative data and in an experimental condition the spectators were presented with both live locative data and heart rate data. Spectators who were presented with additional heart rate visuals were more likely to support the athletes and submitted more comments to the site. These results support existing literature, indicating that observing another's heart rate data can increase engagement and connectedness between the data sharer and the data viewer. We discussed emerging insights from the results along the main themes that are grounded in the data, and highlighted implications for future designs. In summary, we find that the heart rate representation may enhance the supporters' perception of the effort that is exerted by the athletes. Second, supporters may feel that there is an increase in self-disclosure on the part of the athlete sharing the heart rate data. Third, real-time data from sensors may be perceived as more trustworthy than other traditional self curated content such as text messages. The increase in engagement that those spectators who were presented with heart rate data experienced, has several implications for design practitioners in this area. These implications are relevant for multidisciplinary areas including marketing, ethics and the study of general human behavior. Further research is needed to examine spectators' understanding of heart rate, and why its understanding, or lack of it, influences the behavior of remote others.

Acknowledgments

This research was supported by HighWire, a post-disciplinary programme at Lancaster University funded by the UK Digital Economy Programme (EP/G037582/1). This work also received support from the UK Research Council through the Catalyst project, (EP/I033017/1).

References

Armstrong, S. (2007). Wireless connectivity for health and sports monitoring: a review. *British journal of sports medicine*, 5(41):285–289.

Bae, S., Jang, J., and Kim, J. (2013). Good Samaritans on social network services: Effects of shared context information on social supports for strangers. *International Journal of Human-Computer Studies*, 71(9):900–918.

Baumeister, R. F., Bratslavsky, E., Finkenauer, C., and Vohs, K. D. (2001). Bad is stronger than good. *Review of general psychology*, 5(4):323–370.

Bernstein, M. S. (2010). Crowd-powered interfaces. In *UIST '10: Adjunct proceedings of the 23nd annual ACM symposium on User interface software and technology*, pages 347–350. ACM Press.

Bolchini, C., Curino, C. A., Orsi, G., Quintarelli, E., Rossato, R., Schreiber, F. A., and Tanca, L. (2009). And what can context do for data? *Communications of the ACM*, 52(11):136–140.

Campbell, R. and Schram, P. J. (1995). Feminist Research Methods: A Content Analysis of Psychology and Social Science Textbooks. *Psychology of Women Quarterly*, 19(1):85–106.

Caulfield, P. (2012). Felix Baumgartner 'didn't feel anything' when he broke the sound barrier - NY Daily News.

Chamberlain, A., Crabtree, A., Rodden, T., Jones, M., and Rogers, Y. (2012). Research in the Wild: Understanding 'In the Wild' Approaches to Design and Development. In *Designing Interactive Systems*, pages 795–796, New York, New York, USA. ACM Press.

Chung, C. F., Dew, K., Cole, A., Zia, J., Fogarty, J., and Kientz, J. A. (2016). Boundary Negotiating Artifacts in Personal Informatics: Patient-Provider Collaboration with Patient-Generated Data . *CSCW'16*.

Curmi, F., Ferrario, M. A., Southern, J., and Whittle, J. (2013). HeartLink: open broadcast of live biometric data to social networks. In *CHI'13: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 1749–1758. ACM Press.

Curmi, F., Ferrario, M. A., and Whittle, J. (2014). Sharing real-time biometric data across social networks. In *DIS'14: Proceedings of Designing Interactive Systems*, pages 657–666, New York, New York, USA. ACM Press.

Daignault, P., Soroka, S., and Giasson, T. (2013). The Perception of Political Advertising During an Election Campaign: A Measure of Cognitive and Emotional Effects. *Canadian Journal of Communication*, 38(2):167–185.

Dey, A. K. (1998). Context-aware computing: The CyberDesk project. In *1998 Spring Symposium on Intelligent Environments*, pages 51–54.

Epstein, D. A., Jacobson, B. H., and Bales, E. (2015). From "nobody cares" to "way to go!". In *Proceedings of the 18th Computer Supported Cooperative Work (CSCW)*. ACM Press.

Galily, Y. (2014). When the Medium Becomes "Well Done": Sport, Television, and Technology in the Twenty-First Century. *Television & New Media*, 15(8):717–724.

Grundy, B. L., Crawford, P., Jones, P. K., Kiley, M. L., Reisman, A., Pao, Y.-H., Wilkerson, E. L., and Gravenstein, J. S. (1977). Telemedicine in critical care: An experiment in health care delivery. *Journal of the American College of Emergency Physicians*, 6(10):439–444.

Hallberg, J., Svensson, S., Ostmark, A., Lindgren, P., and Synnes, K. (2004). Enriched media-experience of sport events. In *Sixth IEEE Workshop on Mobile Computing Systems and Applications*. IEEE.

Janssen, J. H., Bailenson, J. N., IJsselsteijn, W. A., and Westerink, J. H. D. M. (2010). Intimate heartbeats: Opportunities for affective communication technology. *IEEE Transactions on Affective Computing*, 1(2):72–80.

Kissling, E. A. (1996). Bleeding Out Loud: Communication about Menstruation. *Feminism & Psychology*, 6:481–504.

Konberg, T., Ohult, C., and Delsing, J. (2003). Measuring breathing- and heart rate data with distribution over wireless IP networks. In *2003 Instrumentation and Measurement Technology Conference (IMTC 2003)*, pages 888–891. IEEE.

Kurvinen, E., Lähteenmäki, M., Salovaara, A., and Lopez, F. (2007). Are You Alive? Sensor data as a resource for social interaction. *Knowledge, Technology & Policy*, 20(1):39–49.

Lee, C. P. (2007). Boundary Negotiating Artifacts: Unbinding the Routine of Boundary Objects and Embracing Chaos in Collaborative Work - Springer. *Computer Supported Cooperative Work (CSCW)*.

Li, I., Dey, A., and Forlizzi, J. (2010). A stage-based model of personal informatics systems. *CHI 2010*, pages 557–566.

McCarthy, J. (1993). Notes on Formalizing Context. In *IJCAI'93: Proceedings of the 13th international joint conference on Artifical intelligence*, pages 555–560. ACM Press.

Miller, L. C., Berg, J. H., and Archer, R. L. (1983). Openers: Individuals who elicit intimate self-disclosure. *Journal of personality and social psychology*, 44(6):1234–1244.

Mitra, T., Hutto, C. J., and Gilbert, E. (2015). Comparing Person- and Process-centric Strategies for Obtaining Quality Data on Amazon Mechanical Turk. In *CHI '15: Proceedings of the ACM Conference on Human Factors in Computing Systems*, pages 1345–1354. ACM Press.

Mueller, F., Agamanolis, S., and Picard, R. (2003). Exertion interfaces: sports over a distance for social bonding and fun. In *CHI'03: Proceedings of the ACM Conference on Human Factors in Computing Systems*, pages 561–568. ACM Press.

Mueller, F., Vetere, F., Gibbs, M. R., Edge, D., Agamanolis, S., and Sheridan, J. G. (2010). Jogging over a distance between Europe and Australia. In *UIST'10: Proceedings of the ACM symposium on User interface software and technology*, pages 189–198. ACM Press.

Nihal, F. G. and Elif, D. U. (2002). Theory and Applications of Biotelemetry. *Journal of Medical Systems*, pages 159–178.

Nord, J., Synnes, K., and Parnes, P. (2002). An architecture for location aware applications. In *SS'02: Proceedings of the International Conference on System Sciences*, pages 3805–3810. IEEE.

O'Brien, S. and Mueller, F. F. (2007). Jogging the distance. In *CHI'07: Proceedings of the ACM Conference on Human Factors in Computing Systems*, pages 523–526, New York, New York, USA. ACM Press.

Perttula, A., Tuomi, P., Suominen, M., Koivisto, A., and Multisilta, J. (2010). Users as Sensors: Creating Shared Experiences in Co-creational Spaces by Collective Heart Rate. In *MindTrek'10*, pages 41–48, New York, New York, USA. ACM Press.

Poh, M. Z., McDuff, D. J., and Picard, R. W. (2010). Non-contact, automated cardiac pulse measurements using video imaging and blind source separation. *Optics Express*, 18(10):10762–10774.

Polanyi, M. (2009). *The Tacit Dimention*. University of Chicago Press, 1 edition.

Qingbin, W. (2009). Statistical analysis on the enterprise logo color designs of global 500. In *Computer-Aided Industrial Design & Conceptual Design*, pages 277–280. IEEE.

Rogers, Y. (2011). Interaction design gone wild: striving for wild theory. *Interactions*, 18(4).

Schnadelbach, H., Irune, A., Kirk, D., Glover, K., and Brundell, P. (2012). ExoBuilding: Physiologically Driven Adaptive Architecture. *Transactions on Computer-Human Interaction (TOCHI*, 19(4):25:1–22.

Schnädelbach, H., Rennick Egglestone, S., Reeves, S., Benford, S., Walker, B., and Wright, M. (2008). Performing thrill: designing telemetry systems and spectator interfaces for amusement rides. In *CHI'08: Proceedings of the ACM Conference on Human Factors in Computing Systems*, pages 1167–1176. ACM Press.

Slovák, P., Janssen, J., and Fitzpatrick, G. (2012). Understanding heart rate sharing: towards unpacking physiosocial space. In *CHI'12: Proceedings of the ACM Conference on Human Factors in Computing Systems*, pages 859–868. ACM Press.

Snyder, J., Matthews, M., Chien, J., and Chang, P. F. (2015). Moodlight: Exploring personal and social implications of ambient display of biosensor data. In *Proceedings of the 18th Computer Supported Cooperative Work (CSCW)*. ACM Press.

Soleymani, M., Lichtenauer, J., Pun, T., and Pantic, M. (2012). A multimodal database for affect recognition and implicit tagging. *IEEE Transactions on Affective Computing*, 3(1):42–55.

Tennent, P., Reeves, S., Benford, S., Walker, B., Marshall, J., Brundell, P., Meese, R., and Harter, P. (2012). The machine in the ghost: augmenting broadcasting with biodata. In *CHI'12: Proceedings of the ACM Conference on Human Factors in Computing Systems*, pages 91–100. ACM Press.

Walker, B., Schnadelbach, H., Egglestone, S. R., Clark, A., Orbach, T., Wright, M., Ng, K. H., French, A., Rodden, T., and Benford, S. (2007). Augmenting amusement rides with telemetry. In *ACE'07*, pages 115–122. ACM Press.

Wang, P. Y., Qu, A. I., and Rang, H. G. (1992). A multiparameter telemetering system used in shell rowing study. *Engineering in Medicine and Biology Society*, pages 1287–1288.

Worthy, M., Gary, A. L., and Kahn, G. M. (1969). Self-disclosure as an exchange process. *Journal of personality and social psychology*, 13(1):59–63.