Stepping Into the Next Decade of Ubiquitous and Pervasive Computing: UbiComp and ISWC 2021

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The 2021 ACM International Joint Conference on Pervasive and Ubiquitous Computing (UbiComp 2021) took place from September 21–26 virtually, around the world; co-located with the International Symposium on Wearable Computers (ISWC). This article discusses some of the interesting research published in the Proceedings of the ACM on Interactive, Mobile, Wearable, and Ubiquitous Technologies , as well as those accepted at ISWC this year—presented virtually with Live Q&A over Whova, Zoom, and Gather.Town. Furthermore, it covers some of the interesting plenary events, such as the Keynotes by Cynthia Breazeal (MIT Media Labs) and John LePore (Perception), as well as the panel discussion on the 30th anniversary of Mark Weiser's paper on the Vision of a Computer for the 21st Century. Finally, some of the interesting highlights from the ISWC gadget-show and design-exhibition, alongside multiple virtual workshops as part of the adjunct program have been presented.

In this conference-summary paper, we present a comprehensive summary of the main tracks and plenary events for The *2021 ACM International Joint Conference on Pervasive and Ubiquitous Computing* (UbiComp 2021), colocated with the *International Symposium on Wearable Computers* (ISWC 2021) which took place from September 21–26. UbiComp is a premier interdisciplinary venue in which leading international researchers, designers, developers, and practitioners in the field present and discuss novel results in all aspects of ubiquitous and pervasive computing. This includes the design, development, and deployment of ubiquitous and pervasive computing technologies and the understanding of human experiences and social impacts that these technologies facilitate. Held online virtually this year, the conference attracted more than 600 participants and highlighted a total of 35 papers that featured a variety of recent technologies ranging from theoretical contributions to practical applications in ubiquitous and pervasive computing as well as wearable computing.[1]

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PLENARY SESSIONS

Hosting plenary sessions for a live audience across the world in multiple time zones can be quite challenging. However, gather.town and Whova made the experience quite interactive and interesting in a mixed-reality conference, such as UbiComp 2021. Some of the important plenary-session highlights are presented herein.

Keynotes

The conference began with two interactive keynotes—one by Cynthia Breazeal (MIT Media Lab, USA) and the second by John LePore (Perception, USA). In the first keynote by Cynthia on *"Emotion, Social Robots, and a New Human-Robot Relationship,"* she highlighted a number of research projects[2, 3] where she is developing, fielding, and assessing social robots in homes, schools, and hospitals.[4] They have explored different embodiments[4] and developed adaptive algorithmic capabilities for robots to sustain interpersonal engagement and personalize the same to people's needs to support novel interventions in education and emotional wellness.

In the second keynote, John LePore gave a talk on *Future Prototyping for Superheroes, Hypercars, and Emerging Tech*. John LePore leads the team at Perception with an unusually specific focus: Designing fictional technologies seen in film and bringing a similar approach to real-world digital product design. He spoke about the relationship between science-fiction and science-fact, and explained how his team approaches projects ranging from the pragmatic requirements of designing in-car tech for the new Hummer EV, and the blue sky opportunities of designing the technology for the film Black Panther.

Panel: 30th Anniversary of Weiser's Article

Twenty-five years ago, Mark Weiser wrote *"The most profound technologies are those that disappear"* in his paper *"The Computer for the 21st Century,"*[5] proceeding to inspire generations of research in ubiquitous computing. Prof. Gregory Abowd set the stage, asking panelists and community members to recount stories of the profound effect Weiser's article first had on them. He followed up, asking the panelists what developments Weiser had not foreseen. While many felt that Weiser had predicted the future as closely, several insightful comments were made illustrating otherwise. Prof. Abowd took this opportunity to take a facetious tone in an effort to stimulate a back and forth discussion, claiming he would not assign students to read this foundational article as it is too old and no longer relevant to the future of Ubicomp, probing for disagreement. This led to a thoughtful conversation about the nature of teaching the next generation of Ubicomp researchers. Finally, Prof. Abowd asked for the best resources for new researchers to learn from. Panelists noted the talk *"You and Your Research"* by Richard Hamming, *"The Age of Surveillance Capitalism"* by Shoshana Zuboff, and *"Tools for Conviviality"* by Ivan Illich, rounding out the insightful panel discussion.

Social Events Gather Town

A plethora of events were held across various timezones on gather.town—a metaverse or virtual layer over the physical world where conference attendees could socialize, interact, and stream keynotes, paper sessions, and panel discussions throughout the conference days. The three key events were the ISWC gadget-show, ISWC design-exhibition, and the Awards Ceremony for UbiComp/ISWC 2021. The Gadget Show was held at gather.town in a free format to present the latest Gadgets to the Wearable and UbiComp community. It was moderated by Prof. Tom Martin (Virginia Tech, USA), Wayne Piekarski (Google), and Shuyi Sun (UC Davis, USA).

The ISWC Design Exhibition 2021 paraded works in technology worn on the body, such as on-body sensing and sensor networks; responsive technologies for fashion and aesthetics; body extensions, such as bionic limbs and smart prosthetics; wearables for professional use, mobile healthcare, or entertainment; wearability and interaction; and mobile interaction with devices and systems. The entries were in three categories, viz.

a) *Functional*, where the focus was functionally focused on wearable designs, aimed at using technology to solve a particular problem or meet a specific need;
b) *Aesthetic*, where the presentations were aesthetically focused on wearable designs, aimed at developing an aesthetic or visual effect through the use of technology;
c) *Fiber Arts*, comprising of nonwearable, but textile- or fiber-integrated innovations.

Workshops

There were multiple virtual workshops organized at UbiComp/ISWC 2021 this year. The *9th International Workshop on Human Activity Sensing Corpus and Applications (HASCA)*[6] was organized to share the experiences among current researchers around the challenges of real-world activity recognition, the role of datasets and tools, and breakthrough approaches toward open-ended contextual intelligence. Meanwhile, *WellComp 2021*[7] brought together researchers and practitioners from academia and industry to explore the contribution of ubiquitous computing toward users' well-being that covers physical, mental, and social wellness. While *EarComp 2021*[8] discussed how sensory wearables technologies have and can complement human sensing research, *EyeWear 2021*[9] brought forward large-scale uses of eyewear computing, discussing lessons learned from early deployment and how to empower the community with better hardware/software prototyping tools as well as the establishment of open datasets. The workshop on *Mental Health and Well-being*[10] holds tremendous importance as mental health issues affect a significant portion of the world's population and can result in debilitating and life-threatening outcomes. The workshop discussed the uptake of ubiquitous technologies into clinical mental healthcare. To explore the intersection between data and physical knowledge, the workshop on *Combining Physical and Data-Driven Knowledge in Ubiquitous Computing*[11] brought together domain experts that explore the physical understanding of the data, practitioners that develop systems, and researchers in traditional data-driven domains. The workshop *Making Sense of Emotion Sensing: Workshop on Quantifying Human Emotions*[12] discussed research to critically evaluate whether it is actually possible and in what ways it could be beneficial for technologies to be able to detect user emotions. In parallel, the *Workshop on Reviewable and Auditable Pervasive Systems*[13] aimed to bring together a range of perspectives on how we can better audit and understand the complex, socio-technical systems that increasingly affect us. The meta-workshop, *Wild by Design: Workshop on Designing Ubiquitous Health Monitoring Technologies for Challenging Environments*[14] focused on the challenges of real-world health monitoring deployments to produce forward-looking insights that can shape the way researchers and practitioners think about health monitoring, in platforms and systems that account for the complex environments where they are bound to be used. The workshop *SensiBlend: Sensing Blended Experiences in Professional and Social Contexts*[15] sought to scrutinize and advance the role and impact of Ubiquitous Computing in the new "blended" social reality, and raise questions relating to the specific attributes of socio-technical experiences in the future organization of interpersonal relationships. Finally, *The First Workshop on Multiple Input Modalities and Sensations for VR/AR Interactions*[16] discussed the challenges and applications of designing a higher coherence between different input modalities and sensations to offer more engaging VR/AR experiences, which can create opportunities for the researchers from both UbiComp and VR/AR fields to jointly discuss and brainstorm new directories of designing new input modalities and sensations for VR/AR interactions.

MAIN TRACK

The main track for UbiComp/ISWC 2021 covered a total of 35 papers accepted across multiple issues of IMWUT for 2020–21. The *Proceedings of the ACM on Interactive, Mobile, Wearable, and Ubiquitous Technologies (IMWUT)* publishes peer-reviewed research relevant to pervasive and ubiquitous computing and covers a broad range of topics, such as mobile systems, wearable technologies, and intelligent environments.[1] The scope includes research contributions in systems and infrastructures, new hardware and sensing techniques, and studies of user experiences and societal impact. In addition to this, IMWUT accepts contributions to new methodologies and tools, theories, and models, as well as visionary and survey papers that may help advance the field. The IMWUT and ISWC papers at UbiComp 2021 were presented in four parallel tracks across multiple subdomains in ubiquitous computing and HCI.

With multiple presentation sessions for IMWUT and ISWC papers, UbiComp/ISWC 2021 covered a range of topics in the area of mobile, ubiquitous, and wearable computing. In this section, we describe the research work presented this year in the areas of a) *Health and well-being*, b) *Human activity recognition (HAR)*, c) *acoustic and RF sensing*, d) *driving and transportation*, e) *wearable computing and interaction*, f) *emotion, cognition, and human behavior*, g) *activity sensing and gesture recognition*, h) *haptics and wearable interfaces*, and i) *privacy and security*.

Health and Well-being

UbiComp/ISWC has been a forerunner in designing novel technological interventions to protect the health and well-being of both individuals and the collective. This year one of the IMWUT distinguished paper awards went to *"FluSense: A Contactless Syndromic Surveillance Platform for Influenza-Like Illness in Hospital Waiting Areas"* by Forsad Al Hossain and his team.[17] The work demonstrates an unobtrusive and privacy-sensitive way to collect crowd-level bioclinical signals related to physical symptoms of influenza-like illnesses and the design could be leveraged for COVID-related crowd surveillance. This year UbiComp/ISWC spawned with Emotion and Mental Well-being sessions chaired by James Scott, Professors Akane Sano, and Nabil Alshurafa. Most of the work featured stress detection via sensors or via a contactless method (e.g., wireless signals).[18,19] A group led by UW Prof. Shwetak Patel designed and tested a novel mobile app-based solution to interpret the results of rapid diagnostic tests by leveraging image processing technologies.[20]

The Well-being sessions, chaired by Professors Auk Kim and Gang Zhou, presented a diverse set of work ranging from food intake,[21] happiness detection[22] to cognitive fatigue prediction.[23] The researcher group from Koa Health, Spain leveraged outlier values from smartphone sensing data that are otherwise discarded to identify extreme cases of user-perceived happiness.[22]

The Health sessions, chaired by Professors Akane Sano, Nabil Alshurafa, Gang Zhou, and Judy Kay, showcased many interesting works in health and well-being. Many works presented mHealth and smartphone-based solutions for various health issues ranging from controlling drinking behavior among Dysphagia Patients[24] to respiration monitoring[25] and predicting psychological constructs[26] among others. Varun Mishra and his team presented a chatbot-based digital coach to predict when a person is the most receptive to Just-In-Time Adaptive Health Interventions.[27] Other work highlighted wearable technologies for health interventions, such as sleep apnea detection,[28] diabetes management,[29] facial expression,[30] and physiological measurement[31] among others.

In addition, there were three workshops around, which are given in the following:

1) *Wellness and computing (WellComp)*,
2) *Mental well-being and emotion sensing (Making Sense of Emotion Sensing)*, and
3) (*Mental Health and Well-Being*.

These workshops discussed how ubiquitous computing is shaping users' physical, mental, and social wellness; how computing is quantifying human emotions and what could be the rationale behind it; and finally, how computing is tracking and revealing clinically relevant behaviors, symptoms, and contexts that permeate users' mental health and well-being.

Human Activity Recognition

Novel research in HAR pushed the frontier in creating massive datasets through a huge breadth of paradigms and techniques, while also introducing novel applications and approaches. Many researchers noted the success in computer vision and natural language processing that had been built on massive datasets of millions of samples and suggested that much more powerful HAR algorithms can be built if the community could collect larger datasets or better leverage existing data.

Several works leverage existing HAR datasets to improve algorithm performance. Cai *et al.*[32] augmented existing datasets for RF-based sensing of human-motion-related activities by simulating RF data from publicly available video data, of which there are large amounts, providing larger datasets for RF-based sensing algorithms to learn from. Tang *et al.*[33] augmented HAR datasets through a semisupervised training scheme, SelfHAR, that leverages unlabeled data that is easier to collect in most HAR applications using a teacher–student self-training and multitask self-supervision scheme. Ma *et al.*[34] used deep clustering to enforce an interpretable latent feature representation, which can leverage-unlabeled data to train HAR systems. Md. Rabiul Islam *et al.*[35] adapted self-supervised learning methods for cognitive HAR tasks like reading, illustrating how self-supervised learning can accelerate progress toward real-world implementation. Lago *et al.* [36] proposed a method for improving single-sensor-based activity recognition by leveraging data from multiple sensors during training time. In a method reminiscent of domain adaptation, the proposed method transforms the data from the various training sensors into a shared representation space. This multiplies the available training data for models using the shared representation space as input.

Many of the research presented also sought to improve accessibility or engagement during data collection. Mairittha *et al.*'s[37] work aim to improve data collection efforts for HAR systems through an active learning system that gamifies data collection and implements an inaccuracy detection module to ensure data quality. Chen *et al.*[38] explored various methods of alleviating HAR data collection by reducing boredom during data collection to facilitate longer data collection periods and using unique feedback structures to incentivize higher quality participant-provided labels. Yan *et al.*[39] experimented with various HAR data collection interfaces on smartwatches that are less burdensome than traditional interfaces. During Q&A, the authors highlighted the need for larger HAR datasets to train powerful machine learning algorithms.

Several novel techniques and applications for HAR were presented as well. Akther *et al.*[40] designed a system for detecting which teeth surfaces are being brushed based on wrist-worn inertial sensors, to identify inadequately brushed areas, and intervene to improve brushing habits. The session chair, Thomas Ploetz, noted the long, challenging process of collecting data and overcoming technical challenges in completing the work. Wang *et al.*[41] designed a novel HAR-protective behavior detection (PBD) architecture that recognizes the behavior context to apply the optimal PBD method to serve people with chronic pain during physical activities. Hiremath *et al.*[42] augmented HAR practitioner's ability to understand HAR task complexity through an objective task complexity assessment. All of these works represent great strides toward ubiquitous HAR.

Acousting and RF Sensing

This year's UbiComp/ISWC featured a rich breadth of acoustic and RF sensing work, ranging from enabling multitarget LoRa sensing to sensing with smart speakers. Dr. Abhinav Mehrotra, Dr. Lin Wang, Dr. Cheng Zhang, Dr. Wayne Piekarski, and Dr. Junehwa Song led the discussions in the five sessions on acoustic sensing. Dr. Stephan Sigg, Dr. Vaishnavi Ranganathan, and Dr. Zimu Zhou led the discussions in the three sessions on RF sensing.

The acoustic sensing sessions showcased how researchers enabled acoustic sensing to make a real-world impact. Zhang *et al.*[43] from the Institute of Software in the Chinese Academy explored how wireless sensing could be an effective alternative to health monitoring. They sought to evaluate if smart speakers could monitor health signals, such as respiration and heart rate as accurately as the traditional PPG and ECG devices. Their results suggested that smart speakers can provide accurate and contact-free respiration and heart rate monitoring. Li *et al.*[44] from the University of New South Wales presented the challenges in drone usage, including unauthorized drone intrusions and attacks. As a countermeasure, they proposed *DronePrint*, an acoustic-based system that detected and identified drones. Their findings suggested that the *DronePrint* system can be effective in detecting drones for known and unknown classes as well as identifying their manufacturers. Jin *et al.* from the University of Buffalo introduced *SonicASL*.[45] The author discussed the importance of gesture recognition for the hearing-impaired population. Unlike the traditional sensor- and camera-based gesture recognition, their work proposed a more natural way to recognize hand gestures using acoustic signals. The results presented suggest that the *SonicASL* achieves better hand gesture recognition when the distance is small, but the accuracy of the *SonicASL* was impacted largely by distance and angle.

A major theme of the RF-sensing section was exploiting the limitations of existing hardware. Xie *et al.* [46] pushed the limits of LoRa by enlarging target-induced signal variations. Liang *et al.* challenged the limitation of mmWave sensing by uncovering hidden signal patterns across multiple antennas.[47] Katanbaf *et al.* developed a backscatter system that exploits various signal sources to enable a reliable coverage of backscatter connectivity in multipath-rich, indoor environments.[48] In addition to exploiting hardware capabilities, session presenters showcased their effort to enable novel applications, such as approximating the traditionally bulky Synthetic Aperture Rader imaging with mmWave,[49] recognizing the shape and material of an object simultaneously and noninvasively through RFID tag, and sensing liquid level in a container utilizing existing home WiFi network.[50] Presenters were specifically keen on clinical and health applications, such as vital sensing,[51] infusion drip rate monitoring,[52] and long-range multitarget respiration sensing.[53]

Driving and Transportation

Over the past few years, there has been an increasing interest in *ubiquitous transportation systems*. In UbiComp/ISWC 2021, the "Driving and Transportation" session mainly discussed real-world problems, such as demand forecasting,[54] heterogeneous-agent dynamic resource allocation (HADRA),[55] accurate physical locations estimation,[56] energy-efficient logistic delivery,[57] and crowdsourced delivery system.[58] For the demand forecasting problem, Luo *et al.*[54] proposed a graph neural network-based spatio-temporal pattern recognition approach. The qualitative analysis gains significant performance enhancement over state-of-the-art methods and it is robust toward perturbations. Zhao *et al.*[55] formulated the existing issue of *"multiple cars chasing one spot"* as HADRA problem by considering the parking demand, associated demands, and constraints. The solution comprises a two-stage resource allocation, i.e., multistep parking prediction and diversified parking. The real-time deployment also indicates the efficiency of the proposed method in terms of time and resource requirements. To cope with the increasing demand of the logistic industry, prior algorithms end up with energy-inefficient last-mile delivery. To overcome this issue, Pan *et al.*[57] presented a delivery scheduling algorithm, which is optimized for time and number of parcels. Similarly, Ding *et al.*[58] incorporated a low-cost crowdsourced delivery system while considering practical factors, such as time constraints, multihop delivery, and profits. The quantitative deployment suggests that the profit and delivery rates are increased by a significant margin. Given a large-scale database of merchants, there is a high chance of error for accurate physical locations estimation. On this front, *ALWAES*[56] proposes five different spatio-temporal strategies to highlight the important tradeoffs. This year, the driving and transportation session is conducted in three different sessions with five paper presentations followed by Q&A. During

Q&A session audience is interested in *self-driving e-bikes* and their cost, the *requirement of a joint parking mechanism,* and *reflection on the reason behind the less usage of car sharing among women*. Finally, the degree of ubiquity in terms of driving, mobility, and transportation intelligence will evolve from a low level to a high level for improving the efficiency, bias, safety, and mobility in transportation with the advancement of technology.

Wearable Computing and Interaction

This year's paper sessions for *wearable interaction* covered a broad scope of applications ranging from mental health analysis, signal acquisition, attention-aware eyewear technology, and antispoofing devices. UbiCAT[59] is a smartwatch-based tool to monitor attention, working memory, sleeping pattern, and other important functions for mental health diagnosis. During the Q&A session, the audience was interested in the *possibility of misdiagnosis* and *transferability* in the mental health domain. Although anyone cannot ignore the possibility of misdiagnosis, the proposed method has the potential to overcome several real-world deployment challenges. On the other hand, the transferability of the method is not certain at the moment, as other mental disorders may vary in symptom characteristics. McDonald *et al.*[60] explored the possibility of real-time deployment of knitted capacitive sensors by introducing signal acquisition, signal processing, and temporal pattern analysis. The audience was curious about the *reuse* of the system for other interaction domain. However, the model requires training for adapting to the new environment. MemX[61] is a smart eyewear system to "record everything a person sees" in real-time and in an energy-efficient way. As the deployment environment is considered to be in the city, the audience was curious about *rural environment deployment* along with its *generalizability*. With the consideration of a wide range of challenges, such as fast scenes, very complex scenes, and scenes with many people, MemX generalizes well in any environment. DualRing[62] proposed two ring-shaped input devices to capture hand-to-surface and hand-to-object interaction. Moreover, the dual ring system is more efficient and novel for sensing comprehensive gestures. Zhao *et al.*[63] developed an antispoofing sensing channel prototype compatible with RFID, Wi-Fi, and acoustic signals for preventing possible attacks in voice systems. Extensive experiments on six different environments suggest the superiority of the proposed design. During Q&A, *the robustness of the system in presence of external noise along with its threshold limit* was asked. However, the study does not consider environmental noise in the framework.

Contributions in *wearable computing* have taken great strides to simplify the production pipeline of wearables and their electronic composites. Cost, processing, production time, resource demands, and electronic waste are just a few of the perennial issues being confronted by this year's papers. Wang *et al.*[64] created an integrated design, simulation, and fabrication workflow called MorphingCircuit, which combines electronic functions with forms through four-dimensional printing to fabricate 3D electronics, addressing not only the concerns mentioned above but also the challenges in compatibility that often occurs when working with complex geometries. Another study developed a novel system for end-to-end design and fabrication of customized functional self-contained hand wearables called FabHandWear.[65] Paredes *et al.* identified the obstacles posed by the broad variations of size and form found in hands and responded with highly customizable hand wearables that work seamlessly with off-the-shelf electronics.

Wide-scale developments in the design and validation of wearable technology involve comprehensive surveying of the present methods being employed, as well as their potential points for improvement. A comprehensive survey conducted by Lambrichts *et al.*[66] delved into existing interactive and ubiquitous device prototyping toolkits and systematically analyzed their characteristics within a novel taxonomy. As a result, the authors introduced a new and holistic way of evaluating toolkits that cover matters, such as "ease of construction" and "ease of moving from prototype to product." This tackles the often inconsistent reporting of the less technical characteristics of prototyping toolkits. In a similar domain, Baronetto *et al.*[67] streamlined the process of evaluating garment-embedded contact sensors through activities of daily living (ADL) simulation, automated smart garment design, dynamic 3D human body model generation, and dynamic sensor fitting and sensor displacement simulation. The study generated 100 3D human body models of varying body shapes and virtually dressed them in three differently fitted smart T-shirts. Results showed a decrease in sensor distance while BMI increased for both sexes. This method is particularly useful in evaluating contact sensor performance for different body shapes, ADLs, and garment designs.

Emotion, Cognition, and Human Behavior

A significant focus was devoted to cognition and human behavior in this year's UbiComp/ISWC, as human cognition has a high correlation with technological usage front. There are sessions regarding *emotion and mental well-being* and *cognition and human behavior,* which consist of ∼5 papers each. The *emotion and mental well-being* paper session mainly covers smartphone distraction management system,[68] smartphone-based mood measuring toolkit,[69] “Empathetic Car”[70] and “Mindless Load Changer.”[71] For designing a smartphone distraction management system,[68] rule-based mining method is incorporated, which utilizes the end-user’s perception to overcome the limitation of the existing strategies, and makes them more sustainable. Similarly, the smartphone-based mood measuring toolkit[69] requires less prior information to improve certain mental conditions, such as user dissatisfaction and fatigue. The design also considers adaptive strategies that can capture mood fluctuations on both a daily and weekly basis. “Empathetic Car”[70] monitors the driver’s emotion, comfort, well-being, and safety. To overcome privacy concerns, the sensor data obtained from smartphones is used to estimate the affective state of the driver. The “Mindless Load Changer”[71] studies the unconscious reaction of the user while viewing myoelectricity sensor information which also demonstrates the existence of the psychological phenomenon that can manipulate the load perception. On the other hand, *cognition and human behavior* session mainly discusses cognitive performance using physiological and facial features,[72] game as a measurement environment,[73] a longitudinal study on public roads for in-vehicle well-being,[74] cognitive load measurements in aviation (especially in mixed virtual and physical flight environment),[75] and social context of alcohol drinking in young adults.[76] During the Q&A session, the audience was curious about *if the technology inherently keeps the locus of control away from the individual* and *lower receptivity of results*. In future, these technologies could be used in a wide scale, which could further facilitate healthy mental well-being.

Activity Sensing and Gesture Recognition

This year’s notable contributions in *Activity Sensing* sought to address common obstacles in everyday electronics. In response to the challenge of efficient text entry on smartwatches, Zhang *et al.* developed WriteAS,[77] a natural and expressive input method for smartwatches that uses inertial sensors to capture hand movements. Results of their testing showed that WriteAS performed effectively on different types of smartwatches and surfaces. In the realm of smartphones and similar devices in which face touch events are of particular importance, Kakaraparthi *et al.* introduced FaceSense,[78] a sensing method for determining hand-to-face proximity or hand motion.

Gesture Recognition regularly faces the formidable task of collecting large amounts of user data in order to perform certain functions. Several papers have put forward solutions through convolution neural networks, user-agnostic data, and position-independent sensing. mHomeGes,[79] a real-time mmWave arm gesture recognition system, distills arm gesture positions, and their dynamic variations into a lightweight convolution neural network capable of recognizing fine-grained gestures. The system confronts enduring problems, such as limited gesture space, localized interferences, and lack of offline recognition. A similar method is proposed by Suzuki *et al.*,[80] where personal classifiers are used to synthesize gesture examples of the target class from a target user in order to reduce the use of gesture samples and extensive user calibration without sacrificing accuracy.

In another method, Li *et al.* do away with having target users altogether. CrossGR,[81] a low-cost and cross-target gesture recognition system, interprets human gestures without the need for prior knowledge of the target user. It uses a deep neural network that extracts user-agnostic, gesture-related Wi-Fi signal characteristics and serves as an answer to the expensive process of collecting training data from every single user. While Wi-Fi received signal patterns are useful in mapping human activities, the practice is position-dependent; Gao *et al.* tackled this through motion navigation primitive,[82] a position-independent sensing strategy that captures directional changes and movement patterns of the hand and converts these gestures into sequences of strokes, allowing them to be recognized easily.

Haptics and Wearable Interfaces

Research into underutilized areas for gesture recognition also came to the fore in this year’s conference proceedings. StruGesture,[83] a fine-grained gesture recognition system for the back of mobile phones, explores back-of-device sensing possibilities by using structure-borne sounds to recognize sliding gestures. This differs widely from existing systems that can only handle coarse-grained gesture recognition, which is easily impacted by interference in the air. Results showed that StruGesture outperforms competitive state-of-the-art classifiers with an average recognition accuracy of 99.5% in 10 gestures.

Further applications in haptics and kinesthetic communication show promise in expanding the usability of adjacent technologies that could either benefit from or make use of additional sensing. Gu *et al.*,[84] for example, approached the lack of support for touch-based text entry in an alternate reality and virtual reality (AR/VR) headsets and smart TVs through QwertyRing, a technique for supporting text entry on physical surfaces. By using an inertial measurement unit ring, users can type on any desk-like surface as if there were a QWERTY keyboard present and do not need to monitor their hand motions in the process. In another study, Ikematsu *et al.* [85] sought to leverage capacitative touch sensing through ScraTouch, an input modality that extends the interaction technique of fingernails.

Many tactile and wearable interfaces face significant barriers due to the length of time necessary to master the technology and the difficulty that it takes to design them. Carson *et al.*[86] conducted a literature review on existing sensory substitution and augmentation devices (SSAD) to examine their metrics for success and growing influence on interface design in order to widen their adoption in studies on human–computer interaction. SSADs can help create rich, immersive human–computer interactions, and hybrid visual and haptic feedback mechanisms have been shown to enable greater haptic signal comprehension.

Haptics also possess the potential for impacting emotion research. Foo *et al.*[87] explored the capacity of wearable haptic garments to communicate emotions, whether it be as a supportive tool in research, as a bolster for better social interactions, or as a means of improving immersive entertainment experiences. Shape-memory alloys (SMAs) can provide coupled warmth and compressive sensations in a single actuation, indicating that it may be able to act as a proxy for human touch. Their work endeavored to map out a design space for SMA-based garment-mediated emotional communication using warm, compressive actuation. They were able to determine five major categories of mental models: Representation of body sensations, replication of typical social touch strategies, metaphorical representation of emotions, symbolic representation of physical actions, and mimicry of objects or tasks.

Privacy and Security

Due to rapid progress in ubiquitous technology over the past few years, its usage in different domains has increased significantly. However, the extensive usage of technology raises privacy and security concerns. This year UbiComp hosted *"Security and Authentication"* and *"Privacy"* to highlight these concerns. The *"Security and Authentication"* session contains six papers, which mostly discuss authentication, probable attacks, and design space in the biometric-based authentication system. Krasovec *et al.*[88] proposed an IoT testbed to gather behavior data, such as a person's movement in space, interaction with certain physical objects, PC terminal usage, keyboard typing etc., which further can be analyzed for authentication purpose. In another paper, a behavior biometrics-based authentication system[89] can be deployed in a smartphone's pattern lock. Similarly, Kumar *et al.*[90] proposed *Aquilis*, a smartphone-based privacy protection system on this front. On the other hand, the *"Privacy"* session discusses different aspects of privacy concerns in this domain, including privacy-preserving customization framework for edge computing,[91] privacy implications in location tracking,[89] spatial privacy risks in mobile-mixed reality data,[92] location privacy in crowd-sensing photos[93] and privacy-preserving federated learning.[94] In the Q&A session, the audience was interested in *"thread modeling," "generalization of Aquilis modeling,'* 'and *"adversarial geo-identification"* concerns regarding location images and *"one's privacy preferences*." In the future, it is important to consider the privacy issues for any system/model.

REFERENCES

1. *ISWC '21: 2021 Int. Symp. Wearable Comput.*, Assoc. Comput. Mach., New York, NY, USA, 2021.
2. I. Rahwan *et al.*, "Machine behaviour," *Nature*, vol. 568, no. 7753, pp. 477–486, 2019.
3. C. Breazeal, "Emotion and sociable humanoid robots," *Int. J. Hum. Comput. Stud.*, vol. 59, no. 1–2, pp. 119–155, 2003, doi: 10.1016/S1071-5819(03)00018-1.
4. R. Williams, S. P. Kaputsos, and C. Breazeal, "Teacher perspectives on how to train your robot a middle school AI and ethics curriculum," in *Proc. AAAI Conf. Artif. Intell.*, vol. 35, no. 17, pp. 15678–15686, 2021.
5. M. Weiser, "The computer for the 21st century," *ACM SIGMOBILE Mobile Comput. Commun. Rev.*, vol. 3, no. 3, pp. 3–11, 1999.
6. K. Murao *et al.*, "9th International workshop on human activity sensing corpus and applications (HASCA)," in *Proc. Int. Joint Conf. Pervasive Ubiquitous Comput.*, 2021, pp. 281–284.
7. T. Okoshi, J. Nakazawa, J. G. Ko, F. Kawsar, and S. Pirttikangas, "WellComp 2021: Fourth Int. Workshop on Computing Well-Being," in *Proc. UbiComp '21, Adjunct Proc. ACM Int. Joint Conf. Pervasive Ubiquitous Comput. Proc. ACM Int. Symp. Wearable Comput.*, 2021, pp. 108–111, doi: 10.1145/3460418.3479262.

8. F. Kawsar, R. Harle, A. Montanari, and C. Min, "EarComp 2021: Second Int. Workshop on Earable Computing," in *Proc. UbiComp '21: Adjunct Proc. ACM Int. Joint Conf. Pervasive Ubiquitous Comput. Proc. ACM Int. Symp. Wearable Comput.*, 2021, pp. 135–138, doi: 10.1145/3460418.3479263.
9. K. Ragozin *et al.*, "Eyewear 2021: The forth workshop on eyewear comput—Augmenting social situations and democratizing tools," in *Proc. UbiComp '21: Adjunct Proc. ACM Int. Joint Conf. Pervasive Ubiquitous Comput. Proc. ACM Int. Symp. Wearable Comput.*, 2021, pp. 458–461, doi: 10.1145/3460418.3479267.
10. V. Mishra *et al.*, "6th International Workshop on Mental Health and Well-Being: Sensing and Intervention," in *Proc. UbiComp '21: Adjunct Proc. ACM Int. Joint Conf. Pervasive Ubiquitous Comput. Proc. ACM Int. Symp. Wearable Comput.*, 2021, pp. 185–187, doi: 10.1145/3460418.3479264.
11. W. Ding, C. Wu, and W. Xu, "CPD 2021: The 4th Int. Workshop Combining Physical Data-Driven Knowledge in Ubiquitous Computing," in *Proc. UbiComp '21: Adjunct Proc. ACM Int. Joint Conf. Pervasive Ubiquitous Comput. Proc. ACM Int. Symp. Wearable Comput.*, 2021, pp. 586–588, doi: 10.1145/3460418.3479270.
12. B. Tag *et al.*, "Making sense of emotion-sensing: Workshop on quantifying human emotions," in *Proc. UbiComp '21: Adjunct Proc. ACM Int. Joint Conf. Pervasive Ubiquitous Comput. Proc. ACM Int. Symp. Wearable Comput.*, 2021, pp. 226–229. doi: 10.1145/3460418.3479272.
13. C. Norval, R. Cloete, M. Markovic, I. Naja, and K. B. Cornelius, "Workshop on Reviewable and Auditable Pervasive Systems (WRAPS)," in *Proc. UbiComp '21: Adjunct Proc. ACM Int. Joint Conf. Pervasive Ubiquitous Comput. Proc. ACM Int. Symp. Wearable Comput.*, 2021, pp. 261–263 doi: 10.1145/3460418.3479265.
14. D. Branco *et al.*, "Wild by design: Workshop on designing ubiquitous health monitoring technologies for challenging environments," in *Proc. UbiComp '21: Adjunct Proc. ACM Int. Joint Conf. Pervasive Ubiquitous Comput. Proc. ACM Int. Symp. Wearable Comput.*, 2021, pp. 508–510, doi: 10.1145/3460418.3479271.
15. H. Verma, M. Constantinides, S. Zhong, A. El Ali, and H. S. Alavi, "Sensiblend: Sensing blended experiences in professional and social contexts," in *Proc. UbiComp '21: Adjunct Proc. ACM Int. Joint Conf. Pervasive Ubiquitous Comput. Proc. ACM Int. Symp. Wearable Comput.*, 2021, pp. 491–495, doi: 10.1145/3460418.3479268.
16. C.-W. You, Y.-C. Chen, H.-R. Tsai, and B. Sheng, "The First Workshop on Multiple Input Modalities and Sensations for VR/AR Interactions (MIMSVAI)," in *Proc. UbiComp '21: Adjunct Proc. ACM Int. Joint Conf. Pervasive Ubiquitous Comput. Proc. ACM Int. Symp. Wearable Comput.*, 2021, pp. 546–549, doi: 10.1145/3460418.3479269.
17. F. Al Hossain, A. A. Lover, G. A. Corey, N. G. Reich, and T. Rahman, "Flusense: A contactless syndromic surveillance platform for influenza-like illness in hospital waiting areas," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 4, no. 1, pp. 1–28, Mar. 2020, doi: 10.1145/3381014.
18. V. Mishra *et al.*, "Evaluating the reproducibility of physiological stress detection models," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 4, no. 4, pp. 1–29, Dec. 2020, doi: 10.1145/3432220.
19. U. Ha, S. Madani, and F. Adib, "Wistress: Contactless stress monitoring using wireless signals," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 3, pp. 1–37, Sep. 2021, doi: 10.1145/3478121.
20. C. Park *et al.*, "The design and evaluation of a mobile system for rapid diagnostic test interpretation," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 1, pp. 1–26, 2021, doi: 10.1145/3448106.
21. L. Meegahapola *et al.*, "One more bite? Inferring food consumption level of college students using smartphone sensing and self-reports," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 1, pp. 1–28, 2021, doi: 10.1145/3448120.
22. T. S. Buda, M. Khwaja, and A. Matic, "Outliers in smartphone sensor data reveal outliers in daily happiness," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 1, pp. 1–19, Mar. 2021, doi: 10.1145/3448095.
23. M. Arthurs, J. J. Dominguez Veiga, and T. E. Ward, "Accurate reaction times on smartphones: The challenges of developing a mobile psychomotor vigilance task," in *Proc. Int. Symp. Wearable Comput.*, 2021, pp. 53–57, doi: 10.1145/3460421.3478818.
24. K. An, Q. Zhang, and E. Kwong, "Viscocam: Smartphone-based drink viscosity control assistant for dysphagia patients," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 1, pp. 1–25, 2021, doi: 10.1145/3448109.
25. J. Liu, Y. Zeng, T. Gu, L. Wang, and D. Zhang, "Wiphone: Smartphone-based respiration monitoring using ambient reflected wifi signals," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 1, pp. 1–19, 2021, doi: 10.1145/3448092.

26. K. Saha *et al.*, "Person-centered predictions of psychological constructs with social media contextualized by multimodal sensing," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 1, pp. 1–32, 2021, doi: 10.1145/3448117.
27. V. Mishra, F. Künzler, J.-N. Kramer, E. Fleisch, T. Kowatsch, and D. Kotz, "Detecting receptivity for mHealth interventions in the natural environment," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 2, pp. 1–24, 2021, doi: 10.1145/3463492.
28. X. Chen, Y. Xiao, Y. Tang, J. Fernandez-Mendoza, and G. Cao, "Apneadetector: Detecting sleep apnea with smartwatches," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 2, pp. 1–22, 2021, doi: 10.1145/3463514.
29. A. Bartolome, S. Shah, and T. Prioleau, "Glucomine: A case for improving the use of wearable device data in diabetes management," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 3, pp. 1–24, 2021, doi: 10.1145/3478109.
30. D. Verma, S. Bhalla, D. Sahnan, J. Shukla, and A. Parnami, "Expressear: Sensing fine-grained facial expressions with earables," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 3, pp. 1–28, 2021, doi: 10.1145/3478085.
31. P. Chwalek, D. Ramsay, and J. A. Paradiso, "Captivates: A smart eyeglass platform for across-context physiological measurement," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 3, pp. 1–32, 2021, doi: 10.1145/3478079.
32. H. Cai, B. Korany, C. R. Karanam, and Y. Mostofi, "Teaching RF to sense without RF training measurements," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 4, no. 4, pp. 1–22, 2020, doi: 10.1145/3432224.
33. C. I. Tang, I. Perez-Pozuelo, D. Spathis, S. Brage, N. Wareham, and C. Mascolo, "SelfHAR: Improving human activity recognition through self-training with unlabeled data," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 1, 2021, doi: 10.1145/3448112.
34. H. Ma, Z. Zhang, W. Li, and S. Lu, "Unsupervised human activity representation learning with multi-task deep clustering," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 1, pp. 1–25, 2021, doi: 10.1145/3448074.
35. M. R. Islam *et al.*, "Self-supervised learning for reading activity classification," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 3, pp. 1–2, 2021, doi: 10.1145/3478088.
36. P. Lago, M. Matsuki, K. Adachi, and S. Inoue, "Using additional training sensors to improve single-sensor complex activity recognition," in *Proc. Int. Symp. Wearable Comput.*, 2021, pp. 18–22, doi: 10.1145/3460421.3480421.
37. N. Mairittha, T. Mairittha, P. Lago, and S. Inoue, "CrowdAct: Achieving high-quality crowdsourced datasets in mobile activity recognition," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 1, pp. 1–32, 2021, doi: 10.1145/3432222.
38. W. Chen, S. Lin, E. Thompson, and J. Stankovic, "Sensecollect: We need efficient ways to collect on-body sensor-based human activity data!," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 3, pp. 1–27, 2021, doi: 10.1145/3478119.
39. X. Yan, S. Raj, B. Huang, S. Y. Park, and M. W. Newman, "Toward lightweight In-situ self-reporting: An exploratory study of alternative smartwatch interface designs in context," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 4, no. 4, pp. 1–22, 2020, doi: 10.1145/3432212.
40. S. Akther, N. Saleheen, M. Saha, V. Shetty, and S. Kumar, "Mteeth: Identifying brushing teeth surfaces using wrist-worn inertial sensors," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 2, pp. 1–25, 2021, doi: 10.1145/3463494.
41. C. Wang *et al.*, "Leveraging activity recognition to enable protective behavior detection in continuous data," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 2, pp. 1–27, 2021, doi: 10.1145/3463508.
42. S. K. Hiremath and T. Plötz, "Deriving effective human activity recognition systems through objective task complexity assessment," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 4, no. 4, pp. 1–24, 2020, doi: 10.1145/3432227.
43. F. Zhang, Z. Wang, B. Jin, J. Xiong, and D. Zhang, "Your smart speaker can "hear" your heartbeat!" *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 4, no. 4, pp. 1–24, 2020, doi: 10.1145/3432237.
44. H. Kolamunna *et al.*, "Droneprint: Acoustic signatures for open-set drone detection and identification with online data," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 1, pp. 1–31, 2021, doi: 10.1145/3448115.
45. Y. Jin *et al.*, "SonicASL: An acoustic-based sign language gesture recognizer using earphones," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 2, pp. 1–30, 2021, doi: 10.1145/3463519.
46. B. Xie, Y. Yin, and J. Xiong, "Pushing the limits of long range wireless sensing with LoRa," *Proc. ACM Interact., Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 3, pp. 1–21, 2021.
47. Y. Liang, A. Zhou, H. Zhang, X. Wen, and H. Ma, "FG-LiquID: A contact-less fine-grained liquid identifier by pushing the limits of millimeter-wave sensing," *Proc. ACM Interact., Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 3, pp. 1–27, 2021.

48. M. Katanbaf, V. Jain, and J. R. Smith, "Relacks: Reliable backscatter communication in indoor environments," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 4, no. 2, pp. 1–24, 2020.
49. H. Regmi, M. S. Saadat, S. Sur, and S. Nelakuditi, "SquiggleMilli: Approximating SAR imaging on mobile millimeter-wave devices," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 3, pp. 1–26, 2021.
50. Y. Ren, S. Tan, L. Zhang, Z. Wang, Z. Wang, and J. Yang, "Liquid level sensing using commodity wifi in a smart home environment," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 4, no. 1, pp. 1–30, 2020.
51. J. Gong, X. Zhang, K. Lin, J. Ren, Y. Zhang, and W. Qiu, "RF vital sign sensing under free body movement," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 3, pp. 1–22, 2021.
52. Y. Lin, L. Xie, C. Wang, Y. Bu, and S. Lu, "Dropmonitor: Millimeter-level sensing for RFID-based infusion drip rate monitoring," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 2, pp. 1–22, 2021.
53. F. Zhang *et al.*, "Unlocking the beamforming potential of LoRa for long-range multi-target respiration sensing," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 2, pp. 1–25, 2021.
54. M. Luo, B. Du, K. Klemmer, H. Zhu, H. Ferhatosmanoglu, and H. Wen, "D3P: Data-driven demand prediction for fast expanding electric vehicle sharing systems," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 4, no. 1, pp. 21:1–21:21, 2020, doi: 10.1145/3381005.
55. D. Zhao, Z. Cao, C. Ju, D. Zhang, and H. Ma, "D2park: Diversified demand-aware on-street parking guidance," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 4, no. 4, pp. 163:1–163:25, 2020, doi: 10.1145/3432214.
56. D. Jiang *et al.*, "ALWAES: An automatic outdoor location-aware correction system for online delivery platforms," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 3, pp. 107:1–107:24, 2021, doi: 10.1145/3478081.
57. Y. Pan *et al.*, "Efficient schedule of energy-constrained UAV using crowdsourced buses in last-mile parcel delivery," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 1, pp. 28:1–28:23, 2021, doi: 10.1145/3448079.
58. Y. Ding *et al.*, "A city-wide crowdsourcing delivery system with reinforcement learning," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 3, pp. 97:1–97:22, 2021, doi: 10.1145/3478117.
59. P. Hafiz, K. W. Miskowiak, A. Maxhuni, L. V. Kessing, and J. E. Bardram, "Wearable computing technology for assessment of cognitive functioning of bipolar patients and healthy controls," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 4, no. 4, pp. 129:1–129:22, 2020, doi: 10.1145/3432219.
60. D. Q. McDonald, R. Vallett, E. Solovey, G. Dion, and A. Shokoufandeh, "Knitted sensors: Designs and novel approaches for real-time, real-world sensing," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 4, no. 4, pp. 145:1–145:25, 2020, doi: 10.1145/3432201.
61. Y. Chang *et al.*, "MemX: An attention-aware smart eyewear system for personalized moment auto-capture," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 2, pp. 56:1–56:23, 2021, doi: 10.1145/3463509.
62. C. Liang, C. Yu, Y. Qin, Y. Wang, and Y. Shi, "DualRing: Enabling subtle and expressive hand interaction with dual IMU rings," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 3, pp. 115:1–115:27, 2021, doi: 10.1145/3478114.
63. C. Zhao, Z. Li, H. Ding, W. Xi, G. Wang, and J. Zhao, "Anti-spoofing voice commands: A generic wireless assisted design," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 3, pp. 139:1–139:22, 2021, doi: 10.1145/3478116.
64. G. Wang *et al.*, "MorphingCircuit: An integrated design, simulation, and fabrication workflow for self-morphing electronics," vol. 4, no. 4, pp. 1–26, 2020, doi: 10.1145/3432232.
65. L. Paredes *et al.*, "FabHandWear: An end-to-end pipeline from design to fabrication of customized functional hand wearables," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 2, pp. 1–22, 2021, doi: 10.1145/3463518.
66. M. Lambrichts, R. Ramakers, S. Hodges, S. Coppers, and J. Devine, "A survey and taxonomy of electronics toolkits for interactive and ubiquitous device prototyping," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 2, pp. 1–24, 2021, doi: 10.1145/3463523.
67. A. Baronetto, L. Uhlenberg, D. Wassermann, and O. Amft, "Simulation of garment-embedded contact sensor performance under motion dynamics," in *Proc. Int. Symp. Wearable Comput.*, 2021, pp. 73–77, doi: 10.1145/3460421.3480423.
68. I. Kim, H. Goh, N. Narziev, Y. Noh, and U. Lee, "Understanding user contexts and coping strategies for context-aware phone distraction management system design," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 4, no. 4, pp. 134:1–134:33, 2020, doi: 10.1145/3432213.

69. H. Torkamaan and J. Ziegler, "Mobile mood tracking: An investigation of concise and adaptive measurement instruments," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 4, no. 4, pp. 155:1–155:30, 2020, doi: 10.1145/3432207.
70. S. Liu *et al.*, "The empathetic car: Exploring emotion inference via driver behaviour and traffic context," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 3, pp. 117:1–117:34, 2021, doi: 10.1145/3478078.
71. T. Futami Seki and K. Murao, "Mindless load changer: A method for manipulating load perception by feedback of myoelectricity sensor information," in *Proc. ACM Int. Symp. Wearable Comput.*, D. Roggen, K. Vega, and H. C. Kao, Eds., 2021, pp. 58–62, doi: 10.1145/3460421.3478816.
72. S. W. T. Chan, S. Sapkota, R. Mathews, H. Zhang, and S. Nanayakkara, "Prompto: Investigating receptivity to prompts based on cognitive load from memory training conversational agent," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 4, no. 4, pp. 121:1–121:23, 2020. doi: 10.1145/3432190.
73. T. Miura *et al.*, "GAME: Game as a measurement environment: Scheme to evaluate interfaces and game contents based on test theories," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 4, no. 4, pp. 166:1–166:30, 2020, doi: 10.1145/3432702.
74. K. Koch *et al.*, "When do drivers interact with in-vehicle well-being interventions?: An exploratory analysis of a longitudinal study on public roads," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 1, pp. 19:1–19:30, 2021, doi: 10.1145/3448116.
75. J. C. Wilson, S. Nair, S. Scielzo, and E. C. Larson, "Objective measures of cognitive load using deep multi-modal learning: A use-case in aviation," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 1, pp. 40:1–40:35, 2021, doi: 10.1145/3448111.
76. L. Meegahapola, F. Labhart, T. Phan, and D. Gatica-Perez, "Examining the social context of alcohol drinking in young adults with smartphone sensing," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 3, pp. 121:1–121:26, 2021, doi: 10.1145/3478126.
77. Q. Zhang, D. Wang, R. Zhao, Y. Yu, and J. Jing, "Write, attend and spell: Streaming end-to-end free-style handwriting recognition using smartwatches," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 3, pp. 1–25, Sep. 2021, doi: 10.1145/3478100.
78. V. Kakaraparthi *et al.*, "Facesense: Sensing face touch with an ear-worn system," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 3, pp. 1–27, 2021, doi: 10.1145/3478129.
79. H. Liu *et al.*, "Real-time arm gesture recognition in smart home scenarios via millimeter wave sensing," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 4, no. 4, pp. 1–28, 2020, doi: 10.1145/3432235.
80. N. Suzuki, Y. Watanabe, and A. Nakazawa, "GAN-based style transformation to improve gesture-recognition accuracy," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 4, no. 4, pp. 1–20, 2020, doi: 10.1145/3432199.
81. X. Li *et al.*, "CrossGR: Accurate and low-cost cross-target gesture recognition using Wi-Fi," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 1, pp. 1–23, 2021, doi: 10.1145/3448100.
82. R. Gao *et al.*, "Towards position-independent sensing for gesture recognition with Wi-Fi," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 2, pp. 1–28, 2021, doi: 10.1145/3463504.
83. L. Wang *et al.*, "Watching your phone's back: Gesture recognition by sensing acoustical structure-borne propagation," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 2, pp. 1–26, 2021, doi: 10.1145/3463522.
84. Y. Gu, C. Yu, Z. Li, Z. Li, X. Wei, and Y. Shi, "QwertyRing: Text entry on physical surfaces using a ring," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 4, no. 4, pp. 1–29, 2020, doi: 10.1145/3432204.
85. K. Ikematsu and S. Yamanaka, "ScraTouch: Extending interaction technique using fingernail on unmodified capacitive touch surfaces," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 4, no. 3, pp. 1–19, 2020, doi: 10.1145/3411831.
86. I. Carson, A. Quigley, L. Clarke, and U. Hinrichs, "Investigating the effect of sensory concurrency on learning haptic spatiotemporal signals," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 1, pp. 1–30, 2021, doi: 10.1145/3448102.
87. E. W. Foo, L. E. Dunne, and B. Holschuh, "User expectations and mental models for communicating emotions through compressive & warm affective garment actuation," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 1, pp. 1–25, 2021, doi: 10.1145/3448097.
88. A. Krasovec, D. Pellarini, D. Geneiatakis, G. Baldini, and V. Pejovic, "Not quite yourself today: Behaviour-based continuous authentication in IoT environments," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 4, no. 4, pp. 136:1–136:29, 2020, doi: 10.1145/3432206.
89. D. Shi *et al.*, "Fine-grained and context-aware behavioral biometrics for pattern lock on smartphones," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 1, pp. 33:1–33:30, 2021, doi: 10.1145/3448080.

90. A. Kumar, T. Braud, Y. D. Kwon, and P. Hui, "Aquilis: Using contextual integrity for privacy protection on mobile devices," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 4, no. 4, pp. 137:1–137:28, 2020, doi: 10.1145/3432205.
91. B. Liu, Y. Li, Y. Liu, Y. Guo, and X. Chen, "PMC: A privacy-preserving deep learning model customization framework for edge computing," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 4, no. 4, pp. 139:1–139:25, 2020, doi: 10.1145/3432208.
92. J. A. de Guzman, A. Seneviratne, and K. Thilakarathna, "Unravelling spatial privacy risks of mobile mixed reality data," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 1, pp. 14:1–14:26, 2021, doi: 10.1145/3448103.
93. T. Zhou, Z. Cai, and F. Liu, "The crowd wisdom for location privacy of crowdsensing photos: Spear or shield?," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 3, pp. 142:1–142:23, 2021, doi: 10.1145/3478106.
94. B. Khalfoun, S. B. Mokhtar, S. Bouchenak, and V. Nitu, "EDEN: Enforcing location privacy through re-identification risk assessment: A federated learning approach," *Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol.*, vol. 5, no. 2, pp. 68:1–68:25, 2021, doi: 10.1145/3463502.

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