Report from Dagstuhl Seminar 25422

Cognitive Sensing and Interaction

Thomas Kosch*[1], Kai Kunze*[2], Christina Schneegass*[3], and Thad Starner*[4]

1 **HU Berlin, DE.** thomaskosch90@gmail.com
2 **Keio University – Yokohama, JP.** kai@kmd.keio.ac.jp
3 **TU Delft, NL.** c.schneegass@tudelft.nl
4 **Georgia Institute of Technology – Atlanta, US.** thadstarner@gmail.com

Abstract

This report documents the Dagstuhl Seminar "Cognitive Sensing and Interaction" (25422). The report consists of an executive summary, as well as abstracts on talks, working groups, panel discussions, and open problems sessions.

Seminar October 12–15, 2025 – https://www.dagstuhl.de/25422
2012 ACM Subject Classification Human-centered computing
Keywords and phrases cognition-awareness, cognitive augmentation, cognitive interaction, physiological interaction, wearable technology
Digital Object Identifier 10.4230/DagRep.15.10.75

1 Executive Summary

Thomas Kosch (HU Berlin, DE)
Kai Kunze (Keio University – Yokohama, JP)
Christina Schneegass (TU Delft, NL)
Thad Starner (Georgia Institute of Technology – Atlanta, US)

In Human-Computer Interaction (HCI), cognitive sensing offers valuable insights into the relationship between users and technologies, enabling new forms of interaction. Monitoring human cognitive processes, such as attention, memory, and decision-making, enables technologies to adapt to user needs, provide personalized support, and develop new methods for measuring user experience. Such data streams allow for seamless communication between humans and computing systems. With recent advances in Artificial Intelligence (AI), we observe significant improvement in one of the major hurdles in cognitive interaction – the precise and reliable classification of cognitive states. However, critical challenges remain before cognitive interaction can be effectively used in real-world environments. This Dagstuhl Seminar "Cognitive Sensing and Interaction" (25422) focused on three of those challenges, namely (a) robust cognitive sensing in everyday life, (b) how to augment human cognitive abilities efficiently, (c) how to design ethical, inclusive, reproducible systems for a diverse population. The goals of this seminar was to identify successful practices, develop a research agenda, and initiate the development of policy documents for designing user-centric technologies that perceive, communicate with, and engage with user cognition. We brought together experts in HCI, neuroscience, AI, and psychology to synthesize solutions for overcoming challenges and discuss ways to integrate cognitive sensing and interaction into our everyday lives.

* Editor / Organizer

Cognitive Sensing and Interaction, *Dagstuhl Reports*, Vol. 15, Issue 10, pp. 75–104
Editors: Thomas Kosch, Kai Kunze, Christina Schneegass, and Thad Starner
DAGSTUHL REPORTS Dagstuhl Reports
Schloss Dagstuhl – Leibniz-Zentrum für Informatik, Dagstuhl Publishing, Germany

This Dagstuhl Seminar, "Cognitive Sensing and Interaction" (25422), examined how cognitive sensing can transition from lab prototypes to everyday systems that use cognitive interaction. The overarching goal was to discuss the technical feasibility, identify interaction concepts worth pursuing, and determine the necessary governance as sensing technologies mature. The seminar consisted of two keynotes and three days of structured work. The keynotes discussed public-facing use scenarios for personal brain scanners (schools, neurodiversity support, aging) and the move from basic monitoring toward low-power, on-device intelligence enabled by neuromorphic computing. Day 1 mapped sensing modalities and devices to feasibility, including usefulness trade-offs and consolidated metrics, as well as best practices for in-the-wild inference, with an emphasis on multimodal, context-aware interpretation and individualized baselines. Day 2 translated visions into concrete interaction scenarios through rapid prototyping and walk-and-talk ideation, exposing constraints around signal quality, calibration, latency, and how to communicate uncertainty. Day 3 synthesized technical, societal, and legal risks into actionable policy directions and stakeholder responsibilities. The seminar outcomes include an initial framework connecting signals to cognitive constructs and interaction mechanisms, a portfolio of grounded scenarios and design tensions, and a governance agenda centered on transparency, user control, minimal retention, and accountable evaluation beyond accuracy.

2 Table of Contents

3 Overview of Talks

3.1 Smart Sensing and Visualization of Human Mobility Experience

Esther Bosch (DLR – Braunschweig, DE)

My research investigates how human cognitive, emotional, and experiential states can be measured, understood, and visualized across diverse mobility contexts. Whether traveling by public transport [1], driving a car [2], operating a train [3], or cycling through the city, people continuously experience the mobility system not only as infrastructure but as lived experience. Capturing these experiences systematically offers a powerful way to identify where change in the mobility system is most urgent. To this end, I combine valid and reliable subjective measures of travel experience with physiological and contextual data. These include signals from the cardiovascular system, facial expressions, and electrodermal responses, alongside real-world context such as location, time, and traffic conditions. By linking subjective, contextual and physiological indicators, my work aims to model and visualize travel experience dynamically, enabling transport providers, cities, and communities to see mobility from the traveler's perspective [4]. The broader goal is to make human experience a measurable and actionable component of mobility planning, guiding decisions toward more sustainable and user-centered systems. In the long term, I envision experience measurement that requires minimal user input, grounded in a deep understanding of the relationship between subjective experience and physiological signals. This approach bridges human factors research, psychophysiology, and mobility data science to make the invisible dimensions of travel, such as goal-relevant hindrances, experience compared to expectations, and overall traveler state, visible and usable for design and policy.

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3.2 Beyond Measurement: Designing Cognitive and Digital Technologies that Support Work and Wellbeing

Anna Cox (University College London, GB)

My research explores how digital technologies can be designed and used to support both work and wellbeing. I am particularly interested in the bidirectional relationship between productivity and health: how the very technologies that enable us to work, such as communication, planning, and collaboration tools, can also be harnessed to promote wellbeing, and how the technologies we use to manage our health and wellbeing can, in turn, enhance our effectiveness at work. A major interest is the use of psychological theory to inform the design and evaluation of these digital systems. By grounding technology design in established theories of motivation, self-regulation, and recovery, I aim to deepen our understanding of how people interact with these systems and how technology can be shaped to foster thriving rather than overwork. In related work, I have examined how digital systems for measuring and evaluating work can shape experiences of productivity and control, particularly in remote and hybrid contexts. For example, in Remote Work, Work Measurement and the State of Work Research in Human-Centred Computing (Gould et al., 2023), we argued that the expansion of "bossware" and digital surveillance during the pandemic highlights the conceptual limits of technology-mediated understandings of work, and the need for more inclusive, representative approaches to future-of-work research. Within the context of this Dagstuhl Seminar, my interests lie in how insights from psychology and human–computer interaction can inform the responsible development of cognitive and physiological sensing technologies for everyday work. This includes questions of boundary management, trust, and ethical design, ensuring that systems which sense or augment human cognition do so in ways that respect autonomy, diversity, and wellbeing. My contribution to the seminar focused on connecting insights from psychology and HCI to the design of ethical, inclusive cognitive interaction systems.

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3.3 Reinventing Human Potential through Cognitive Augmentations

Passant Elagroudy (DFKI – Kaiserslautern, DE)

My research investigates how we can augment human memory and research cognition. A major thread in my work focuses on cognitive alterations – from memory augmentation to attenuation and implantation – enabled by ubiquitous and immersive technologies [1, 2]. I previously explored how technology can act as a partner in remembering – helping people to reconstruct, reinterpret, or even reform their past experiences. Through studies of visual lifelogs, memory cues, and privacy-preserving prostheses, I examine how digital traces interact with our autobiographical memory and sense of self in real life or in virtual environments [3], revealing both the empowering and altering potentials of "smart" memory systems. More recently, I have turned to Generative AI as a cognitive amplifier for researchers. In collaboration with international HCI researchers, I examine how Large Whatever Models (LWMs) can transform research cycles, automate synthesis, and preserve ubiquitous research artifacts [4, 5]. I envision generative systems as active participants in scientific reasoning and collective memory, capable of extending our cognitive reach and accelerating discovery. Working at the intersection of human-computer interaction, psychology, and AI, I aim to establish hybrid systems that not only augment human memory but also reshape how we conduct, recall, and evolve knowledge. My goal is to design technologies that amplify reflection without erasing human agency – tools that help us remember, reason, and reimagine together.

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3.4 The Future of Wearable Neurotechnology: From Sensing to Neuromorphic Intelligence

Mustafa Hamada (Mendi Innovations – Stockholm, SE)

My work explores how neuroscience, behavioral design, and artificial intelligence can be combined to create technologies that advance cognitive health and mental wellbeing. As Chief Product and Science Officer at Mendi Innovations (Sweden), I focus on translating neuroimaging insights into accessible neurofeedback tools, particularly through fNIRS-based brain training for attention and self-regulation. As Honorary Fellow of Neurotechnology at the University of Nottingham's Brain Data Group, I contribute to research that spans HCI, game design, dynamic system theory, and adaptive neurotechnology, using fNIRS data analysis to study engagement and cognitive load. In parallel, I serve as an Advisor to the REACT project (Responsible AI), that aims at developing responsible, adaptive robotic systems for complex healthcare environments and co-lead an IEEE workstream developing ethical frameworks for mental health technologies. I am also involved in work investigating how at-edge neuromorphic computing and EEG-based sensing can enable low-power, real-time interpretation of neural signals in wearable systems to predict epilepsy seizure onset. Across these domains, my goal is to advance ethical, personalized, and human-centered neurotechnology that meaningfully integrates with everyday life.

3.5 JIZAI Coding: Embodied, Affective, and Autonomous Programming for Inclusive Creators

Masahiko Inami (University of Tokyo, JP)

JIZAI Coding is a research initiative that aims to transcend conventional programming paradigms by integrating embodied interaction, affective and physiological sensing, and co-creative AI to empower users – including those with disabilities – to solve their own challenges through code. In contrast to "vibe coding" as a metaphor for loose prompt-driven generation, JIZAI Coding envisions a resonant, adaptive coding partnership between human cognition, bodily states, and generative systems. Drawing upon the framework of Cognitive Sensing and Interaction (Dagstuhl Seminar 25422) and the notion of gut feelings (the body's tacit cues), this project posits a future where code is not only "written" but felt, synchronized, and lived.

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3.6 Long-Term Cognitive Augmentation

Shoya Ishimaru (Osaka Metropolitan University, JP)

Human cognitive capabilities, such as learning, reasoning, and communicating, can be enhanced through various intervention approaches. While direct physiological interventions, including biofeedback and Transcranial Magnetic Stimulation (TMS) provide immediate cognitive enhancement during active stimulation, their effects might be typically transient and limited to the intervention period. My research proposes an alternative paradigm: achieving sustained cognitive augmentation by developing users' meta-skills through information systems. Our approach leverages sensing technologies, including eye-tracking, physiological sensors, and behavioral analytics to recognize cognitive states during learning activities. By providing real-time feedback on engagement levels, comprehension, self-confidence, and mental workload, these systems enable users to develop metacognitive awareness, the ability to monitor and regulate their own cognitive processes. Systems such as intelligent e-books that adapt content based on reader interest [1], engagement gauges that visualize attention in online meetings [2], and gaze-based word-count trackers for reading with smart eyewear exemplify this approach. Unlike temporary enhancement through direct neural stimulation, cultivating meta-skills creates lasting improvements in cognitive capability, as users internalize strategies for self-regulated learning, attention management, and effective knowledge acquisition that persist beyond system use.

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3.7 Open-source neural wearables for the future of work

Michael Knierim (KIT – Karlsruher Institut für Technologie, DE)

My research focuses on developing human-centered adaptive technologies through innovative neural wearables and large-scale biodata to sustainably enhance productivity, health, and well-being. A strong focus of my work is the development of discreet wearable systems (such as ear-EEG integrated headphones) and scalable software solutions that enable the transition from controlled experiments to everyday environments – solutions that I contribute as open-source resources to the scientific community. Working at the intersection of computer science, information systems, and neuroscience, I bridge wearable technology development with rigorous empirical research. My interdisciplinary approach addresses the fundamental challenge of creating reliable biosensing systems while ensuring these adaptive technologies genuinely serve human needs and well-being. Correspondingly the major theme in my work is understanding human cognitive and affective states through multimodal biosensing in both laboratory and real-world contexts. Through studies combining brain activity (EEG), eye tracking (EOG), heart rate variability (ECG/PPG), and behavioral data, I investigate states like cognitive load, flow, mental overload, and fatigue across settings ranging from controlled laboratory experiments to extended field studies in real-world knowledge work and home office scenarios.

At the Dagstuhl Seminar, I contributed a demonstration of the latest versions and ideas for wearable EEG headphones and explored potentials for novel use case scenarios, technical improvements and ares for collaboration like the use of wearable sensors in human-AI interaction or sensing context data to increase the reliability of everyday neural recordings.

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3.8 Estimating Human's Cognitive Situation using AI and CV

Hideki Koike (Institute of Science Tokyo, JP)

Cognitive sensing is sometimes very difficult and not reliable. In order to obtain reliable data, it is necessary to use relatively big sensors such as fMRI. On the other hand, recent advances in computer vision (CV) technology enables us to estimate human activities by using a small number of cameras. We are currently developing methods of estimating human muscle activities by using images captured by one camera. As a future vision, it might be possible to estimate a human's internal state, not only the muscle activities but also brain activities by monitoring the face, eye gaze, and so on using the power of CV. Also the estimation would be more reliable by integrating with other sensor information such as heart rate, blood pressure, or else, which can be obtained by a small wearable device.

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3.9 Artificial Intelligence for Amplifying Human Perception

Thomas Kosch (HU Berlin, DE)

My research explores how artificial intelligence can become an active collaborator in human perception and cognition. I study how computational models of behavior, physiology, and context can foster mutual understanding between humans and AI systems. By integrating signals from the body, such as interoceptive and proprioceptive cues, into interactive systems, I design and build interfaces that amplify human perception rather than replace it. A central theme in my work is amplified perception, the idea that AI can enhance our awareness of internal and environmental states, enabling more transparent, adaptive, and trustworthy interactions. This approach challenges the notion of AI as a controlling agent and instead positions it as a perceptual partner that co-regulates with the user. Through experimental and prototyping work in extended reality and wearable computing, I explore how feedback loops between humans and AI can enhance decision-making, empathy, and self-regulation. Another theme is understanding how the interaction with AI shapes the mental models and metacognition of users. For example, priming users about an AI augmentation system influences the user's view of their own performance, even when the AI system is non-functional. I refer to this as the placebo effect of AI, which should be carefully investigated when evaluating and deploying interactive AI systems, particularly in terms of user agency.

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3.10 Reflexive Wearables: Turning Physiological Sensing into Human Insight

Kai Kunze (Keio University – Yokohama, JP)

My research explores how physiological sensing can move from passive observation to active participation in human cognition and emotion. I focus on signals from the eyes, skin, and cardiovascular system, studying how they can reveal changes in attention, fatigue, or affective state. Through wearable platforms such as smart eyewear [1], I aim to integrate these signals into feedback systems that help people better understand and regulate their mental and emotional processes.

A major theme in my work is digitalized emotion, the idea that feelings and physiological reactions can be captured, represented, and re-experienced in meaningful ways. This approach opens possibilities for sharing emotional experiences, enhancing empathy, and supporting well-being. At the same time, I explore cognitive augmentation by developing tools that extend perception and awareness through subtle feedback rather than direct control. Working at the intersection of computer science, design, and the arts, I collaborate with engineers, performers, and psychologists to study how technology can act as both mirror and partner. My goal is to establish new forms of human-machine interaction that are reflective, adaptive, and emotionally aware, helping people not only to perform better but also to understand themselves and others more deeply.

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3.11 Inferring Cognition through Oculo-metrics: From Laboratory Research to Real-World Applications

Diako Mardanbegi (American University of Beirut, LB)

Over the past 15 years, my research has focused on how eye movement metrics can be sensed and used for interaction with wearable systems [1, 2]. Decades of work have shown strong links between ocular metrics and cognitive states such as attention, fatigue, mental workload, stress, and focus, as well as neurological conditions. My current interest lies in understanding how these eye movement dynamics can support cognitive augmentation in future wearable technologies.

With the rise of eye-worn XR devices enabling continuous eye tracking, a key challenge is translating controlled lab findings into real-world settings. This issue extends beyond eye tracking: other neuro-sensing modalities like EEG, fNIRS, and EMG face similar gaps. Despite the growing availability of consumer brain-sensing devices (e.g., Mendi, MindWave), the mapping between neural signals and higher-order cognitive states such as focus or workload remains weakly supported. Direct, universal links between these signals and complex cognitive functions are still lacking.

At the Dagstuhl Seminar, we discussed cognitive sensing and augmentation from multiple perspectives, including ethics, diversity and inclusion, and technical challenges. One of the most thought-provoking discussions centered on the fundamental gap between sensing and interpretation. Specifically, cognitive states cannot be inferred in a straightforward, one-to-one manner from individual signals (e.g., "signal X implies cognitive state Y"), as these states are influenced by multiple contextual and individual factors, particularly in real-world environments.

Looking ahead, I envision a more reliable and ecologically valid approach that integrates multiple sources of low-level physiological and neural evidence from eye trackers, brain-sensing devices, and fitness trackers, with contextual information and user feedback. By correlating these multimodal signals with higher-level cognitive states and moods in a holistic, personalized framework, we can better capture individual variability, habits, and subjective experiences. Artificial intelligence will play a critical role in linking these multimodal data streams to cognitive biomarkers and potential health indicators, ultimately enabling more robust and meaningful cognitive augmentation through wearable technologies.

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3.12 Assistive Augmentation: Fundamentally Transforming Human Ability

Suranga Nanayakkara (National University of Singapore, SG)

The rapid development of smart devices and emerging AI capabilities holds immense potential to transform not only our daily interactions but also our pursuit of life goals. Existing user interfaces, however, often fall short of realizing this potential. Individuals with disabilities, who rely heavily on assistive technologies for daily functioning and independence, face significant challenges due to the limitations of current approaches. Consider a person with visual impairment navigating a supermarket. While traditional accessibility features, such as text-to-speech, offer some assistance with shopping, they often require a cumbersome series of interactions, hindering the user's ability to efficiently gather information and make choices. We argue that the perceived separateness and disconnect between accessibility devices and users hinder the experience of true empowerment.

Why is that? I believe that conversations have been overly focused on user-system coexistence and compatibility (e.g., "I will use this device" and "This is a user-friendly device") rather than integration and augmentation of ability (e.g., "This device is a part of me" and "I have evolved with technology to unlock my full potential"). A paradigm shift is needed from viewing technology as a separate tool to considering it as an integrated extension of the human body, mind, and identity. We call this new perspective of human augmentation is called assistive augmentation [1].

Creating such Assistive Augmentations pose a threefold challenge as they require 1) exploring ways to seamlessly integrate into users body or behaviour, 2) deeper understanding of the user so as to provide the right level of support while keeping the user in control 3) holistic design approach to create meaningful applications. Inspired by insights from psychology, human centred machine learning, and design thinking, we have an unprecedented opportunity to design a new generation of Assistive Augmentations.

To highlight this, since 2011, I have been exploring several example project within this theme at the "Augmented Human Lab". This include projects such as "AiSee" [2] that allows blind users to access information simply by pointing at objects and asking questions; "Prospero" [3] a memory training assistant that is able to detect when a user can learn more efficiently; "MuSS-Bits" [4], that allows deaf users to feel the music.

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3.13 Understanding Cognitive Augmentation through the Lenses of Experience, Agency, and Ethics

Jasmin Niess (University of Oslo, NO)

In a world where technology increasingly shapes how we think, feel, and connect, my research asks how we can design interactive systems that genuinely support people's long-term well-being. One key area of my work focuses on cognitive augmentation such as neurotechnologies. I see this as a space for reimagining how humans and technologies can evolve together in ways that extend and enrich our cognitive and emotional capacities over time.

Within this space, my work addresses three interrelated challenges. The first concerns (i) bridging the gap between cognitive sensing data and people's lived experience, for instance, by understanding when and how feedback should be provided and how individuals can create meaningful experiences with and from their data. The second explores (ii) agency and relationship building, examining how people experience agency when augmented and how they perceive such technologies, whether as tools, partners, or even as parts of themselves. The third centres on (iii) diversity, ethics, and regulation, highlighting the need to move beyond the narrow, Western-centric, neurotypical user profiles that dominate much of the current research landscape.

Drawing on my background in HCI and psychology, I develop theories, new measures, and interactive prototypes grounded in psychological knowledge. My work aims to translate conceptual insights into actionable guidance for researchers and practitioners, advancing a vision of technology that supports long-term well-being and meaningful augmentation experiences.

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3.14 AI-Powered Human Augmentation in the Workplace

Evangelos Niforatos (TU Delft, NL)

Evolution has always been the main driving force behind slow but steady change for the human brain and body. However, living in the Information era, our perceptual and cognitive capacities cannot simply rely on natural evolution to keep up with the immense advancements in emerging technologies. Tools we use daily (AI agents, Chatbots, PCs, smartphones, wearables, etc.) remain largely uninformed about our perceptual levels and cognitive states, forming a so-called "cognitive gap" between the human (user) and the machine (system) [1].

My research explores how AI-powered systems can sense and enhance human cognition in real-world productivity contexts, in an attempt to bridge the "cognitive gap" by utilizing physiological sensing, machine intelligence, and human-computer interaction principles. By combining sensing modalities such as EEG [2], eye-tracking [3], and physiological signals with generative and reasoning models, my work aims to interpret and respond to human cognitive processes, such as attention, recall, problem-solving, or creativity in situ. This approach contributes to developing adaptive, cognition-aware interfaces that support decision-making, learning, and productivity without compromising autonomy or well-being.

In the "Cognitive Sensing and Interaction" seminar theme, my interest lies in connecting cognitive sensing with generative AI (GenAI) to create systems that not only infer mental states but also proactively scaffold human cognition. For instance, integrating GenAI with sensed cognitive workload can enable systems that offer context-aware explanations, personalized feedback, or cognitive offloading mechanisms in manufacturing [4], healthcare, and education. Ultimately, this research seeks to advance human-centered cognitive augmentation by integrating intelligent systems into workflows, where AI complements rather than replaces human intelligence.

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3.15 From Perception to Shared Cognition: Leveraging Egocentric Physiological and Behavioral Cues for Empathic Remote Collaboration

Prasanth Sasikumar (National University of Singapore, SG)

Remote collaboration in mixed reality often lacks the rich, implicit signals that ground face-to-face interaction, particularly those tied to cognitive and affective states. My research bridges this gap by integrating real-time physiological sensing with egocentric perceptual data (e.g., eye gaze, hand gestures, and first-person scene understanding) to reconstruct not only the physical workspace but also the cognitive context of collaborators. By fusing signals such as electrodermal activity (cognitive load), heart-rate variability (arousal), and EEG-derived attention with behavioral cues captured from head-mounted sensors, I design systems that support mutual awareness, adaptive communication, and empathic co-experience.

This approach builds on empirical findings showing that sharing combined physiological cues significantly enhances co-presence and social awareness in MR collaboration [1]. Critically, I treat these signals not as isolated metrics, but as interdependent markers of situated cognition: for instance, aligning gaze fixations with spikes in cognitive load can reveal moments of confusion or insight, while synchronizing gesture fluency with attention metrics can indicate confidence or hesitation. Such multimodal inference enables systems that scaffold not just task performance, but shared understanding, turning remote collaboration into a co-regulated cognitive process.

Within the context of the Dagstuhl Seminar on cognition and interaction, I am particularly interested in advancing frameworks that tightly couple perception (what is sensed from the user's egocentric viewpoint) with cognition (what those signals imply about mental state).

My goal is to contribute to a vision of human–machine interaction where technology helps collaborators think and feel together, using egocentric sensing as a foundation for reflective, adaptive, and cognitively attuned remote experiences.

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3.16 Designing Cognition-Aware Interfaces for Neurotechnology

Christina Schneegass (TU Delft, NL)

People are increasingly eager to know more about themselves through technology, which has so far focused on physiological data tracking. Advances in wearable technology and AI are enabling consumer neurotechnology to measure cognitive activity, presenting new research opportunities in Human-Computer Interaction (HCI). I am bringing together knowledge from cognitive psychology, human-centered design, and computer science to explore how we can design interfaces and interaction techniques for cognition-aware technologies – specifically non-invasive consumer neurotechnologies (CNTs). The goal is to help people understand and reflect on cognitive processes, such as focus, stress, and learning, to improve their mental health and well-being. I follow a human-centered approach, studying how people want to engage with cognitive data to design consumer neurotechnologies that respond to people's needs and support healthy reflection.

The seminar topic cognitive sensing and interaction aligns with my research ambitions, especially considering how we can balance inaccuracies in sensing with the users need for explanations and accuracy, in particular when there is a mismatch between objectively sensed data and subjective experiences.

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3.17 Neuroadaptive and Embodied Interfaces for Cognitive Ergonomics

Benjamin Tag (UNSW – Sydney, AU)

My research investigates how technology can extend and refine human cognition through adaptive, embodied interaction. I focus on how mixed and virtual reality systems, combined with physiological sensing, can measure and respond to mental states such as fatigue, attention, and cognitive load. By integrating data from the eyes, muscles, and autonomic nervous system, I aim to build immersive environments that dynamically adjust to users' capabilities, augmenting their awareness, resilience, and performance rather than merely tracking behaviour. A central theme in my work is cognitive ergonomics: understanding how digital systems can support, rather than strain, the human mind. I explore how feedback mechanisms, visual, haptic, or neuroadaptive, can promote sustainable engagement and recovery in cognitively demanding contexts such as training, remote operations, and human-AI collaboration. These systems blur the boundary between observation and augmentation, treating physiological signals as active interfaces that mediate understanding between body and machine. Working across computer science, psychology, and design, I collaborate with neuroscientists, optometrists, and engineers to develop technologies that act not only as tools but as cognitive partners. My goal is to establish a foundation for ergonomic cognitive augmentation: technologies that help humans think, perceive, and adapt more effectively, while preserving well-being and agency in the face of increasing digital complexity.

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3.18 Beyond Enhancement: Cognitive Sensing Futures

Steeven Villa (LMU München, DE)

Augmentation technologies would likely increase adoption in the coming decades, thus understanding their behavioral and societal impacts is critical. My research examines how augmentation technologies influence human behavior and societal dynamics through a prototypical approach [1, 2]: implementing systems, analyzing their effects on human behavior [3] and social contexts [4], and synthesizing insights about short- and long-term impacts. My work has revealed that high expectations of improvement using such technologies increase risk-taking behavior and impact how people physiologically integrate information [5]. Interestingly, my investigation of nocebo effects has shown that these positive responses are resistant to negative narratives, meaning a nocebo effect could not be induced in augmentation technology contexts [6]. This work establishes a foundation for understanding both individual psychological responses and broader societal implications of human augmentation.

The Dagstuhl Seminar on cognitive sensing brought together researchers to address future challenges in this emerging field. I hosted a session exploring the trajectory of cognitive sensing technologies across three timeframes: short (5 years), medium (10 years) and long-term (15+ years). Through structured discussions with seminar attendees, we identified surveillance and potential abuse by corporate or institutional stakeholders as the most critical concerns requiring immediate attention. Specific scenarios that emerged included workplace surveillance and the abuse of physiological data capture to infer people's interests, attention, and cognitive states without consent. The session highlighted that technical advancement must be accompanied by robust alternatives against misuse to ensure responsible development of cognitive sensing technologies.

The insights from the seminar revealed gaps in understanding how unequal access to augmentation technologies shapes society. My next research phase will focus on two interconnected areas: first, analyzing asymmetric interactions between individuals with and without access to augmentation technologies to map societal impacts; and second, developing frameworks for establishing and maintaining trust in augmentation technologies. This work will provide both empirical evidence of technology-driven inequality and practical guidelines for equitable deployment of human augmentation systems.

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3.19 AI-Augmented Cognition and Co-Experience in Extended Reality

Robin Welsch (Aalto University, FI)

My research examines how multimodal sensing and artificial intelligence can make people smarter. I want to combine psychophysiological and behavioral signals, eye movements, electrodermal activity, heart-rate variability, EEG, motion, voice, and context, to infer metacognitive states to build technologies that can support users in self-regulating human-AI interaction. Our recent research could show that metacognition is the bottle neck for performance in human-AI interaction [1] and we know that we can improve performance by adaptive UI by means of physiological sensing [2]. Therefore, I believe that the next step is to build metacognitively-adaptive interfaces to AI.

A second focus is measuring and shaping co-experience in digital environments [3], particularly social XR. I operationalize co-experience as the dynamic coupling of cognitive and affective states across people, quantified through physiological synchrony, and validated reports of presence and co-presence. At Dagstuhl, we have discussed, especially with Kai Kunze, which different analysis strategies and sensors could be used to quantify co-experience.

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3.20 The Future of Cognitive Personal Informatics

Max L. Wilson (University of Nottingham, GB)

My view of consumer neurotechnology is that all of the current innovation is lab experiments and machine learning of datasets for accuracy etc are all a small step in a bigger view of our future living with consumer neurotechnology. This future is one where we have as many apps and wearables for our brain as we do for fitness programmes and long-term health tracking. Physical activity tracking has studied this long-term real-world use of wearable tech in the field of Personal Informatics. I have co-led the community of people that now look at Cognitive Personal Informatics [2, 4, 5] and the impact this will have on the academic landscape [3].

As part of this vision, we began work in 2018, performing longitudinal fieldwork with people tracking their own Mental Workload (as our initial theoretical framework). Initially this was self-reported through an app, and led to our introduction of the Mental Workload Cycle [1] – as a model for people should reach optimal mental effort levels across a whole day. This is distinct from most physical activity tracking that assumes more is always better, but closer to now more expert models of training support that models both activity and recovery.

Our in-progress work now involves longitudinal fieldwork with people that do have viable consumer neurotech. Over the last 12 months, we have engaged in a year of public engagement on consumer neurotechnology. Over 13 events, we have given 5,000 members of the public, teachers, children, parents, lawyers, policy advisors, and politicians the chance to try neurotechnology, and spoken to at least 5,000 more. My research vision is to move first-generation consumer neurotechnology towards devices that help people set goals for the brain, cognitive, and mental health, and can meaningful communicate progress towards them.

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3.21 Co-designing and Personal Fabrication of Assistive Technologies

Anusha Withana (The University of Sydney, AU)

My research focuses on developing personalized wearable technologies that assist individuals with disabilities and chronic health conditions through sensing, actuation, and collaborative physical interactions. A key aspect of this work is engaging end users in the design and fabrication process using co-design tools. This participatory approach ensures that the resulting technologies are not only functional but also meaningful and empowering for the people who use them.

A key aspect that was missing in my research was cognitive considerations of co-design, actuation, and collaborative physical interactions. Critical questions include: How can cognitive sensing enhance creative co-design processes? How do we manage the complexities and adaptability of physical wearable devices wthout cognitive overload? How can cognitive sensing provide better control and agency over wearables? My main goal in attending the seminar was to broaden my research scope to address these challenges and integrate cognitive dimensions into wearable design.

In the seminar, I gained insights into the state of the art in cognitive sensing, both in commercial applications and academic research. I connected with new colleagues for potential collaborations, particularly in embedding cognitive sensing into co-design processes. These discussions opened exciting opportunities to explore how cognitive sensing can enhance accessibility and physical embodiment, how current cognitive sensing technologies can be cp-design and made with personal fabrication approaches and future ethical challenges that are worth exploring in the area.

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4 Working groups

4.1 Envisioning Novel Cognitive Interaction Scenarios

Thomas Kosch (HU Berlin, DE)

The second session was organized as a hike to the remnants of Castle Dagstuhl, with the main goal of creating space for broader and more speculative thinking while still keeping the discussion grounded in cognitive sensing features. The hike was structured as a walk-and-talk activity, where pairs of participants discussed future interaction scenarios and used the movement and changing setting as a deliberate prompt to explore alternatives. We encouraged each pair to focus on a specific context of use, such as collaboration, learning, safety-critical work, or creative tasks, and then to ask what cognitive information could add value in that context and what the associated risks would be.

The discussions moved from the "happy path" to edge cases, for example, what happens when cognitive inferences are wrong, when the user does not want to be sensed, or when the system's adaptation becomes distracting. People also compared scenarios across domains and noticed repeating design tensions, such as personalization versus generalizability, helpful adaptation versus loss of agency, and subtle feedback versus transparency. After returning from the hike, the pairs shared short summaries, which helped us collect a wider set of scenario ideas than we would likely have generated in a room-based format. The outcome was a richer map of possible applications, along with a more explicit understanding of what design constraints and ethical considerations must be addressed early.

4.2 Metrics and Best Practices for Cognitive Sensing

Thomas Kosch (HU Berlin, DE)

During the first session, challenges emerged in utilizing cognitive sensing in everyday contexts, and participants began to share their best practices for ensuring reliability and collecting the most accurate data. In this second session, we built on this discussion by examining measures, analysis approaches, and opportunities and pitfalls across both laboratory and real-world settings. The group discussions were guided by cognitive measures, such as attention, workload, and fatigue, and participants completed the next Miro section. Our later analysis revealed that groups agreed that cognitive data must be collected in a context-aware, multimodal manner and interpreted in relation to an individual's ongoing activity. They emphasized that cognitive data alone is insufficient and must be put into the context of the task, environment, and user state, using other sensor data. Examples for best practices for successful everyday cognitive sensing included feature fusion, motion and noise artifact filtering, data labeling approaches, and multimodal data integration to improve interpretability. Creating individualized baseline measures was also noted as an important best practice, as well as the use of contextual cues. Lastly, participants discussed the opportunities and pitfalls associated with both laboratory and real-world deployments. They noted the benefit of laboratory settings, as they allow for controlled conditions, clear ground truth, and easier sensor management. However, they state that in these conditions, the resulting models might fail if applied outside the laboratory task and setting. In contrast, collecting data in everyday contexts yields more complex observations and higher relevance, but may be challenging to interpret, have power constraints, and raise privacy implications. It is important to consider where the final technology is supposed to be deployed, what the user needs are, and what sensing capabilities are actually needed for it.

4.3 Prototyping Cognitive Interaction Scenarios

Kai Kunze (Keio University – Yokohama, JP) and Thad Starner (Georgia Institute of Technology – Atlanta, US)

The second day began by explicitly extending the third session from the first day, transitioning from a conceptual discussion to concrete interaction scenarios that could be implemented and experienced. Participants brought their own devices and were also provided with hardware on-site, allowing us to directly test ideas rather than just discuss them. We worked in small groups around existing prototypes and early mock-ups, using short iteration cycles. We defined a scenario, decided which cognitive sensing features were assumed to be available, implemented or simulated a minimal interaction, and then reflected on what worked and what broke down.

A recurring focus was on making cognitive sensing actionable in the interaction, for example, by determining what the system should do when it detects a change in attention, workload, or uncertainty, and how that information should be communicated to the user. This hands-on work also highlighted the limitations very clearly. The participants repeatedly encountered questions about signal quality, calibration time, latency, and variability across different people and contexts. By the end of the session, the scenarios were much more specific, including clearer assumptions about sensing reliability, explicit points where uncertainty needs to be communicated, and a better understanding of what kinds of prototypes are feasible to pursue in the short term. The visions were presented by the participants, including a scenario, utopian, and dystopian views.

4.4 Policies for Cognitive Sensing and Cognitive Interaction

Jasmin Niess (University of Oslo, NO) and Thomas Kosch (HU Berlin, DE)

The third day was structured as a single, longer session, intentionally shifting the seminar focus from designing interaction scenarios to the broader question of how cognitive sensing and cognitive interaction technologies should be governed. We began by identifying and unpacking the technical challenges that directly affect both feasibility and risk. Participants discussed the robustness of models outside controlled lab settings, the need for calibration and personalization, sensor noise and missing data, and the fact that many cognitive signals are indirect proxies that can be confounded by context, individual differences, fatigue, stress, or emotion. This led to a discussion of how easily systems can overclaim what they “know” about a user, and why uncertainty needs to be represented explicitly, not only in the model but also in the interaction. We also discussed technical design choices that have policy implications, such as on-device versus cloud processing, what is stored versus processed transiently, and how model updates or domain shifts can alter system behavior over time.

From there, the session expanded to societal and legal challenges, with a focus on what makes cognitive data and cognitive inferences particularly sensitive compared to more traditional forms of interaction data. We discussed risks related to autonomy and manipulation, particularly in settings characterized by power asymmetries, such as workplaces, education, healthcare, and public services. We discussed how the AI act can help with regulating in this context. Furthermore, participants raised questions around consent that is nominally "informed" but not meaningful in practice, especially when sensing is passive or when people cannot realistically opt out. We also reflected on how cognitive interaction techniques could amplify bias or unfairness, for example, when models are trained on non-representative populations or when certain users systematically produce different signals. Legal aspects came up in relation to privacy, data protection, and accountability, including the challenge of regulating not only raw sensor data but also derived inferences about mental states. Even when data is processed locally, the downstream effects of an inference can be high-stakes. Therefore, the group discussed what accountability should look like when harm arises from an adaptive system rather than a single explicit decision.

Based on these discussions, we transitioned into policy ideation with the explicit goal of promoting the benevolent use of cognitive interaction techniques. We brainstormed concrete policy directions, such as requiring clear disclosure when cognitive sensing is active, providing user-facing explanations of what is inferred and at what confidence level, and enabling meaningful user control, including the ability to pause sensing, review what has been collected or inferred, and delete data. Another cluster of ideas focused on minimizing harm by limiting data retention, restricting secondary use, and preventing function creep, for example, avoiding the reuse of cognitive inferences for performance evaluation, targeted persuasion, or surveillance. Participants also discussed the need for deployment constraints, such as stricter requirements for high-risk contexts, stronger oversight when there is an imbalance of power, and explicit rules for when cognitive adaptation should be disallowed or require independent review. Throughout, we have attempted to make these policies actionable by connecting them to implementation mechanisms, such as auditing, documentation requirements, standardized reporting of uncertainty and failure cases, and evaluation protocols that encompass user experience and societal impact, in addition to performance metrics.

In a dedicated part of the session, we then mapped policies to stakeholders and debated who should realistically implement and enforce them. We covered researchers and academic venues, for example, through ethics guidelines, artifact documentation standards, and expectations for responsible evaluation. We discussed how companies build sensing hardware and platforms, as many policy-relevant choices are embedded in default settings, APIs, and data flows. We also included deployers such as employers, schools, and healthcare institutions, who often define the actual usage conditions and incentives. Finally, we considered the role of standards bodies, regulators, and funding agencies in shaping baseline requirements, compliance pathways, and incentives for safer design.

The session concluded with participants writing brief abstracts that summarized their research background and perspectives that contributed to the Dagstuhl Seminar.

4.5 Feasibility of Cognitive Sensing Methods in Everyday Life

Christina Schneegass (TU Delft, NL)

On the first day, we focused on the practical applications of cognitive sensing technologies and asked our participants to share their experiences using them in personal/research settings. Our aim was to collect devices, services, and technologies that work well, as well as those that don't work at all, for everyday situations. We sorted the devices using a feasibility–usefulness matrix using a Miro Board. The participants collected a wide variety of devices and sensing modalities (e.g., wearable neurophysiology, behavioral proxies, environmental sensors). We observed that the experiences of participants, as well as their understanding of what constitutes "reliable," varied among participants. It became clear that the feasibility of using a sensing device outside of laboratory settings depended heavily on the context, the data required, and the protocol. Our participants reported using various research and consumer devices in their practice in everyday contexts, including smartwatches and earbuds. Others, such as EEG and fNIRS, were rated as unreliable outside of laboratory conditions. We further identified challenges that make it difficult to utilize cognitive sensing technologies in the wild, including noise sensitivity, data ambiguity, interpretation challenges, and ethical and privacy concerns (e.g., devices being perceived as surveillance by users rather than as assistance). However, all participants agreed that cognitive sensing technologies must develop to a state where they can be reliably used in everyday contexts to collect valid and reliable data. In essence, this session provided an overview of our seminar participants' experiences with different devices, preferences, and challenges, which we explored in more depth later that day.

4.6 Vision for Cognitive Sensing in 5, 15, and 50 Years

Steeven Villa (LMU München, DE)

Ultimately, our goal was to gather participants' visions for cognitive sensing technologies over the next 5, 15, and 50 years. We asked participants to sketch scenarios using a vignette style and AI-generated visualizations to support their idea. The groups focused on various areas, including ADHD-related support, cognitive monitoring for truck drivers, neural interfaces, emotional regulation tools, and minimally invasive brain-sensing technologies. The 5-year scenarios described ideas for everyday contexts based on research and devices that are (almost) realistic in laboratory settings today. For example, adapting audio environments to improve focus for individuals with ADHD, or detecting fatigue in driving contexts. The 15 and 50-year scenarios were increasingly speculative, embedding cognitive sensing into everyday context (e.g., ubiquitous monitoring, automated workload management), and combining it with neurostimulation for cognitive modulation. Through very precise portable sensing and neural intervention, our groups envisioned that we would be able to suppress disruptions, turn off parts of our brain, and have fully integrated cognition-adaptive personal systems.

4.7 Developing a Framework for Cognitive Interaction

Max L. Wilson (University of Nottingham, GB)

The third session shifted the focus from generating scenarios to establishing shared foundations by discussing what we actually mean by "cognition" in the context of sensing and interaction design. We spent a substantial amount of time aligning terminology, as participants came from different backgrounds and used overlapping terms in varying ways. We discussed how cognition relates to, but is not identical with, constructs such as attention, mental workload, intention, learning, fatigue, affect, and arousal, and we examined where it makes sense to draw boundaries for the purpose of designing interactive systems. This led to a discussion of levels of inference, ranging from low-level signals and proxy measures to higher-level cognitive states and predictions about behavior.

We also talked about the role of context and individual differences, and why a framework needs to represent uncertainty and avoid treating inferred cognition as a stable ground truth. From there, we began shaping the core elements of a framework for sensing cognition, including how sensing signals are mapped to cognitive constructs, how those constructs are represented and updated over time, and how they should influence interaction choices such as feedback, adaptation, and user control. We emphasized that evaluation needs to go beyond classification accuracy and should include user experience outcomes, such as comprehensibility, perceived control, trust, and the consequences of errors. By the end, we established a clearer shared definition to work with and an initial structure that can connect sensing capabilities to interaction mechanisms in a way that is explicit about cognitive assumptions, possibilities, and limitations.

5 Panel discussions

5.1 The Future of Wearable Neurotech: From Sensing to Neuromorphic Intelligence

Mustafa Hamada (Mendi Innovations – Stockholm, SE)

This keynote explores the evolution of consumer neurotechnology from basic monitoring to intelligent, adaptive systems. The $1.8 trillion wellness market is witnessing a paradigm shift toward wearables with clinical efficacy, AI-driven personalization, and continuous bio-monitoring. Current consumer neurotechnology products, such as Mendi, demonstrate how functional near-infrared spectroscopy (fNIRS) can make brain wellness accessible through gamified neurofeedback and cognitive tracking. Existing consumer neurotechnology products face multiple critical limitations, including constrained battery life, reliance on cloud infrastructure raising privacy concerns, and insufficient edge computing for real-time adaptation. The next frontier lies in neuromorphic computing architectures that mimic the brain's own neural efficiency in signal processing. Drawing on principles from dendritic computation, neuromorphic processors consume less than 1% of the power of conventional AI systems while enabling sophisticated on-device intelligence. This enables truly wearable devices such as NEXA Mind for seizure prediction and NEXA Heart for cardiac monitoring systems that operate continuously, privately, and independently of network connectivity. As neurotechnology transitions from clinical to consumer contexts, we must address fundamental questions about meaningful brain engagement, scalable low-power architectures, and safeguarding user agency and trust.

5.2 Our Future Living Scenarios with Personal Brain Scanners

Max L. Wilson (University of Nottingham, GB)

In this presentation, I will reflect on a year of public engagement, during which we gave 5,000 people the chance to experience consumer neurotechnology for the first time and spoke to a further 5,000 people at 13 free science festivals across the UK. In particular, I will unpack the implications raised for scenarios of use and the kinds of meaning people want to make from the data. I will combine these motivating scenarios that came from recent cognitive personal informatics workshops at SIGCHI conferences. The primary novel insights for consumer neurotechnology, especially with respect to non-medical scenarios, were related to use in schools, use by people with neurodiversity, and use by the elderly. Beyond ethical concerns of the use of neurotechnology to enforce learning in schools, there were two occasions where children were happier for neurotechnology to be used in schools: 1) in order for teachers to better understand how neurodivergent learners were behaving, and 2) as feedback to show teachers that their classes are boring. Both of these flip the value to the student's benefit, rather than helping teachers and parents to enforce learning. Neurodivergent people wanted consumer neurotech to help track and understand themselves better, especially to provide evidence that, e.g, "new meds are working". Older users wanted a warning system: one that consumer neurotech would tell them that their brain data looks worrying, and it's time to see a doctor. Aside from these specific cases, common themes were: 1) that people wanted measurement over time, 2) to show progress towards a goal, and 3) that people wanted the associated apps to tell them if their brain data is good or bad. All three of these general points have strong implications for industry and researchers, where relevant goals, showing progress, and recognising good and bad data are all currently unknown.

6 Open problems

6.1 Day 1 Synopsis

Thomas Kosch (HU Berlin, DE), Kai Kunze (Keio University – Yokohama, JP), Christina Schneegass (TU Delft, NL), and Thad Starner (Georgia Institute of Technology – Atlanta, US)

On the first day, we investigated the feasibility, challenges, and future research opportunities of cognitive sensing. Moreover, we investigated how sensing strategies can be translated into interaction concepts. The first session explored the feasibility of cognitive sensing, including various sensing modalities (e.g., eye tracking, electroencephalography, and electrodermal activity), and discussed how they can be realistically integrated into everyday living scenarios. The second session investigated how useful features can be extracted from the discussed sensory measurements. The third session envisioned future interaction concepts.

6.2 Day 2 Synopsis

Thomas Kosch (HU Berlin, DE), Kai Kunze (Keio University – Yokohama, JP), Christina Schneegass (TU Delft, NL), and Thad Starner (Georgia Institute of Technology – Atlanta, US)

The second day extended the third session from the first day by envisioning concrete interaction scenarios. Participants brought and were provided with hardware to test and extend existing prototypes. The second session included a hike to the remnants of Castle Dagstuhl. This hike consisted of a walk-and-talk session, where pairs of participants discussed future interaction scenarios based on cognitive sensing features. The third session focused on unifying a common understanding of cognitive interaction, resulting in a framework for the future.

6.3 Day 3 Synopsis

Thomas Kosch (HU Berlin, DE), Kai Kunze (Keio University – Yokohama, JP), Christina Schneegass (TU Delft, NL), and Thad Starner (Georgia Institute of Technology – Atlanta, US)

The third day focused on the technical, societal, and legal challenges of cognitive sensing and interaction technologies within a longer single session. The participants discussed these challenges and ideated policies to foster benevolent use of cognitive interaction techniques. In this context, participants brainstormed which stakeholders should implement the policies. Lastly, the participants wrote an abstract about their research background, which contributed to the Dagstuhl Seminar.

7 Acknowledgments

This work was partially supported by JST Presto Grant Number JPMJPR2132. Furthermore, this work was supported by the German Research Foundation (DFG), CRC 1404: “FONDA: Foundations of Workflows for Large-Scale Scientific Data Analysis” (Project-ID 414984028).

Participants

- Esther Bosch
DLR – Braunschweig, DE
- Anna Cox
University College London, GB
- Passant Elagroudy
DFKI –
Kaiserslautern, DE
- Mustafa Hamada
Mendi Innovations –
Stockholm, SE
- Masahiko Inami
University of Tokyo, JP
- Shoya Ishimaru
Osaka Metropolitan
University, JP
- Michael Knierim
KIT – Karlsruher Institut für
Technologie, DE
- Hideki Koike
Institute of Science Tokyo, JP
- Thomas Kosch
HU Berlin, DE
- Kai Kunze
Keio University – Yokohama, JP
- Diako Mardanbegi
American University of
Beirut, LB
- Suranga Nanayakkara
National University of
Singapore, SG
- Jasmin Niess
University of Oslo, NO
- Evangelos Niforatos
TU Delft, NL
- Prasanth Sasikumar
National University of
Singapore, SG
- Christina Schneegass
TU Delft, NL
- Tanja Schultz
Universität Bremen, DE
- Thad Starner
Georgia Institute of Technology –
Atlanta, US
- Benjamin Tag
UNSW – Sydney, AU
- Steeven Villa
LMU München, DE
- Robin Welsch
Aalto University, FI
- Max L. Wilson
University of Nottingham, GB
- Anusha Withana
The University of Sydney, AU