Design Science

Design for communication: how do demonstrators demonstrate technology?

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Abstract

The importance of inter- and transdisciplinary research for addressing today's complex challenges has been increasingly recognised. This requires new forms of communication and interaction between researchers from different disciplines and nonacademic stakeholders. Demonstrators constitute a crucial communication tool in technology research and development and have the potential to leverage communication between different bodies of knowledge. However, there is little knowledge on how to design demonstrators. This research aims to understand how demonstrators from the fields Internet of Things and Robotics are designed to communicate technology. The goal is to increase the efficiency and effectiveness of demonstrator practice with readily implemented design knowledge and to advance theoretical knowledge in the field of communicating artefacts. We thematically analysed 28 demonstrator design cases, which led to a typology that assists in categorising and understanding 13 key design principles. The typology is built from three perspectives: First, in terms of the overall goal communication, second, in terms of visitor engagement goals (attraction, initial engagement, deep engagement) and third, in terms of resource-related goals (low effort in development and operation). With this typology, we have taken a significant step towards understanding demonstrator design principles for effective technology communication between different stakeholders.

Keywords: demonstrator design, science communication, technology transfer, interdisciplinary research, boundary object

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1. Introduction

1.1. The demonstrator as communicating artefact

Interdisciplinary and transdisciplinary research has been increasingly recognised as a key mechanism for addressing today's highly complex and multifaceted challenges (Shrivastava *et al.* 2020). However, in reality, conducting research by including scientists from different disciplines and between actors from science and society is difficult (Rhoten 2004; Campbell 2005) and it requires new forms of communication and interaction between them (Hadorn *et al.* 2008; Daedlow *et al.* 2016). One important approach for promoting constructive interaction between stakeholders with different practices and knowledge backgrounds is boundary objects (Vilsmaier *et al.* 2015; Feldhoff *et al.* 2019). The concept, rooted in the field of science and technology studies, provides a lens to better understand why certain artefacts facilitate the cooperation of actors from different social worlds without consensus (Koehrsen 2017). Boundary objects are considered to be both robust enough to carry meaning across different social worlds and plastic enough to adapt to individual interests (Star & Griesemer 1989). This results in enabling the coordination of interests and the generation of knowledge despite heterogeneous constellations.

This study specifically explores the *demonstrator* as a boundary object in the scientific process. The demonstrator (or demonstration – the act of presenting the demonstrator) is an established tool in technology research and development (Bradshaw 2010; Mahmoud-Jouini *et al.* 2013; Moultrie 2015). In academia, it describes an artefact which is created during the scientific process to support science itself, but also the dissemination and communication of it (Moultrie 2015). This becomes tangible at technology-related conferences hosting 'demonstration sessions' for presenting demonstrators (e.g., International Solid-State Circuits Conference or Human–Robot Interaction Conference). However – and surprisingly – very little research can be found, that reflects upon the demonstrator on a meta-perspective, such as its objectives, types or designs. Moultrie (2015) presents one of the few studies that explores the role of the demonstrator in scientific research. He gives insights into the different types of demonstrators that assists the process from basic research until commercialisation. He found evidence that the individual demonstrator can fulfil multiple purposes simultaneously and highlights their important role in science as 'translator objects', communicating between several stakeholders, such as scientists, potential investors and the public. The following example illustrates the possible multitude of purposes and target groups one single demonstrator might serve: to evaluate technology, to present at a scientific conference to support the core scientific messages, to present on public science nights to translate scientific language into a more easily understandable experience, to run scientific experiments with, to present to potential investors during a pitch and to show colleagues from different disciplines during a lab tour. Eventually, the demonstrator serves as a communication tool, potentially resulting in scientific visibility, improved inter- and transdisciplinary research processes, tangible science communication to the public or successful technology transfer to the market (Steen, Buijs & Williams 2014; Moultrie 2015; Lüneburg, Papp & Krzywinski 2020; Bobbe *et al.* 2022).

However, it remains open how demonstrators can be purposefully *designed* to serve as boundary objects and therefore to fulfil their highly communicative purpose. Typically, trained design expertise (in the form of communication, industrial or human–computer interaction design) is rarely involved in scientific processes. Yet, there is evidence of various benefits when engaging designers into the scientific process, not only when technology development is directed towards producing new products for commercialization, but at *any* stage of research. Such benefits include the quick and iterative creation of visualisations and tangible artefacts (prototypes and demonstrators) which serve to support communication, build understanding and enable the testing of ideas (Design Council 2011; Driver, Peralta & Moultrie 2011; Niedderer 2013).

The importance to provide scientists with explicit design knowledge in order to enable them to create effective technology demonstrators becomes clear. This

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research aims to understand the design principles of technology demonstrators from academia by thematically analysing the design of 28 demonstrators. With this study, we aim to advance theoretical knowledge about communicating artefacts in technology development and gain readily implemented design knowledge for designing demonstrators. We first introduce and discuss related artefacts (demonstrator, prototype, science exhibit) and continue with a detailed description of our methodology. We then present the resulting typology and discuss how our work is related to the literature. Finally, we conclude by discussing the limitations of our study and proposing future research.

1.2. Review of related artefacts

Demonstrators are crucial artefacts in technology research and development. When we broaden our view and look at artefacts with similar objectives and contexts as the demonstrator, we find the *prototype* to show substantial similarities. In our view, there is a gap in the literature which results in the absence of a precise demarcation between the concepts prototype and demonstrator. In the following section, we aim to fill this gap by reviewing and contrasting the literature on the prototype and the demonstrator. Eventually, this results in the proposal of a demonstrator definition. Lastly, a third artefact, the *science exhibit* will be introduced and discussed. Distinguishing the roles of the three artefacts supports the theoretical knowledge development assists to interpret the findings of the study.

Prototype

Similar to demonstrators, *prototypes* represent artefacts that are created during research and development processes. Unlike demonstrators, however, there is a large body of knowledge about prototyping, especially in design-related fields of practice and research. Prototypes are physical or digital embodiments of critical elements in the design (Lauff, Kotys-Schwartz & Rentschler 2018). They are used to *explore* and *develop* an idea, a technology or specific attributes of a product. The main goal of prototyping is to inform the design process and design decisions (Buchenau & Suri 2000; Hare *et al.* 2009). It has been argued that prototypes are also used for communication aims because they often represent the earliest embodiment of an idea or a hypothesis (Schrage 1996; Virzi, Sokolov & Karis 1996; Ulrich & Eppinger 2003), however, communication is often limited to clients, potential users and colleagues (Camburn *et al.* 2017). Blomkvist & Holmlid (2011) identified the following consensus concerning the prototype in literature: Prototypes are (a) an embodiment or representation, (b) a hypothesis about the future and (c) that can be evaluated and acted upon.

Demonstrator

Moultrie (2015) mentions the demonstrator as a physical artefact that emerges during technology research and development. He detects different types of demonstrators: They embody science or technology to demonstrate scientific principles, the technical feasibility of potential/specific future applications, commercial feasibility of a specific application or up-scaling in regard to commercialisation. Lastly, demonstrators communicate to convince potential funders or investors and support communication within and outside of the scientific community. Moultrie

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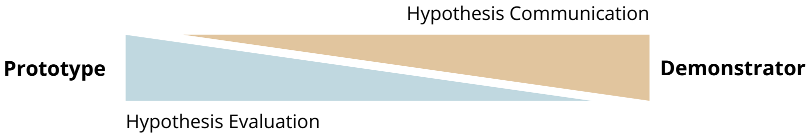

Figure 1. The continuum between the prototype and the demonstrator with different ratios of evaluation and communication purpose.

concludes the paper with mentioning the often-overlooked communicative potential of the demonstrator. However, in his case studies, designers and scientists produced demonstrators *and* prototypes as tangible artefacts and a clear distinction is missing. Mahmoud-Jouini *et al.* (2013) also describe the demonstrator to be a physical artefact in the design process in industry. They found evidence that the demonstrator supports concept evaluation and describes the demonstrator to be an "incomplete and continuously evolving" (p. 15) boundary object, that enables interactions between different stakeholders. Bradshaw (2010) investigated the demonstration activity within industrial product development and identified the demonstration to be a powerful mechanism to engage internal stakeholder and is used as a platform for dialogue and engagement within companies to support the internal innovation process. He considered demonstrators to "provide evidence of product benefits and hence have a primary use as a communication tool" (p. 61). He further describes demonstrators as a platform for evaluation.

We notice a strong overlap of prototypes and demonstrators. However, from the literature mentioned above, we derive that in both settings, science and industry, demonstrators mainly communicate and do not necessarily evaluate an idea about the future, while prototypes do the opposite: they mainly evaluate and not necessarily communicate an idea about the future. In Figure 1, we summarised this crucial differentiation. However, in our view, there is a continuum between the two artefacts without clear delimitation.

To conclude, in the context of our research, we refer to technology demonstrators as (a) an embodiment or representation, (b) of a hypothesis about the future and (c) that is communicated to a specific audience.

Science exhibit

If we approach the demonstrator as communicating artefact from yet another perspective, we find the promising field of museum research, to draw insights from. Interactive science exhibits in informal learning environments share the central purpose with demonstrators: communication of science and technology. We refer to highly interactive science exhibits with the ultimate goal of providing an attractive, engaging and effective learning experience (Dancstep, Gutwill & Sindorf 2015). The literature suggests that visitor engagement with such science exhibits leads to rich learning experiences (Borun & Dritsas 1997; National Research Council 2009; Barriault 2016). Visitor engagement can be defined as the intellectual, physical, social or emotional engagement of visitors (Perry 2012), and enhancing visitor engagement with interactive exhibits has become the primary tool for developing and evaluating exhibits (Ansbacher 2002; Bobbe & Fischer 2022). An engaging exhibit must attract the attention of visitors, have a clear entry point of engagement and encourage prolonged interaction (Hein 2006; Gutwill and

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Figure 2. Visitor Engagement Cycle (after Hein 2006; after Humphrey & Gutwill & Dancstep 2017).

Dancstep (Née Dancu) 2017). This engagement cycle (attraction, initial engagement, deep engagement) (see Figure 2) will be used throughout the study for thematic data analysis.

2. Method

This study describes a thematic data analysis of 28 demonstrator cases to identify the design principles of technology demonstrators in scientific research. Five participants (including the first author) analysed the demonstrator cases, which have been collected through an online survey.

2.1. Collection of demonstrator design cases

To gather first-hand information from demonstrator designers and developers of a large number of demonstrator designs, we created an online survey. To collect as many demonstrator cases as possible in the first place, we did not provide a demonstrator definition, but only stated the context of demonstrators in technology research and development in the introduction of the survey. To understand design approaches of the researchers (intentionally or unintentionally) applied to the demonstrator, but also consider that most researchers are nondesigners, the survey has been built and formulated in a way that no prior design knowledge is required. Thus, questions about the design are divided into subquestions. The final survey contained questions regarding general information concerning the demonstrator (name, institution, duration of development, effort of development), objectives of the demonstrator (primary goals and intentions, secondary goals and intentions, respective target groups and contexts of use), design of the demonstrator (concept, final design) and evaluation of the demonstrator (retrospective evaluation). Respondents could further upload a picture of the demonstrator and leave a website link for further information and their email addresses in the event of questions. The full survey can be found in the Appendix.

The online survey was set up with Lime Survey of the Technische Universität Dresden (https://bildungsportal.sachsen.de/umfragen/limesurvey/). It was open for 8 weeks during 3 September 2021 to 29 October 2021. Invitations to the survey were spread via mail internally (TU Dresden, Cluster of Excellence CeTI) and externally to research institutions, which are known for developing demonstrators during their research process (TU München, DLR, TU Delft, Cambridge, TNO Netherlands, ARS Electronica, Swinburne University of Technology, Barkhausen Institut Dresden, Fraunhofer Institutes). Ninety-one surveys were started, however, only 34 provided comprehensive data. In the following, we applied three exclusion criteria. (a) To align all demonstrators with our proposed definition from above, we applied the communication criteria, which results in the exclusion of cases, which were (so far) used for evaluation purposes only. (b) We further

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excluded demonstrators, which 'failed' in meeting their communication objectives, according to the originators own statements. We added this criterion to ensure a resulting typology with *constructive* design principles. (c) Lastly, we excluded demonstrators, which were still under development and therefore have not yet been evaluated regarding their communication purposes.

As a result, the final sample consisted of 28 demonstrator cases. All demonstrator cases derive from technology research and development in the areas of *Internet of Things* and *Robotics.* Additionally, two-thirds of demonstrator cases derive from one research institution (TU Dresden), but eight different chairs. Nonetheless, this has an effect on the generalisation of the outcome. A condensed overview of all demonstrator cases (including name, originator, objective/s, target group/s and identified design principles) can be found in the Appendix (Tables A1–A4).

2.2. Thematic analysis

We used a thematic analysis to find a comprehensive demonstrator ontology regarding how demonstrators are designed to demonstrate science and technology. It comprises of two parts: (i) Code Generation and (ii) Code Analysis.

(i) Part one consists of a workshop with five participants for initial code generation. All five participants have experience and interest in the design of demonstrators, but derive from different perspectives. With the choice of participants, we included perspectives for two demonstrator purposes, related to communication (Moultrie 2015): communication within the scientific community and communication outside the scientific community (general public, potential funders, industry). Two participants (P2 and P3) are coresearchers.
(P1) Demonstrator design for communication to the general public and scientific community in the field connected robotics, background in electrical engineering, codeveloped two demonstrator cases,
(P2) demonstrator design for communication to potential funders in the field smart wearables, background in industrial design engineering, codeveloped two demonstrator cases,
(P3) demonstrator design for communication to industry in the fields human–machine interface and agriculture, background in industrial design engineering, codeveloped one demonstrator case,
(P4) demonstrator design for communication to potential funders and the general public in the field robotics, background in industrial design engineering, codeveloped one demonstrator case,
(P5) and demonstrator design for communication to the general public in the field tactile internet, background in industrial design engineering, codeveloped two demonstrator cases.

During the 4-hour workshop, we provided a collaborative environment where we negotiated meaning and explicated knowledge (Öberg & Hernwall 2016; Ørngreen & Levinsen 2017). More specifically, we facilitated a group discussion for initial code generation, following a thematic analysis (Braun & Clarke 2006). Every participant screened the data before the workshop. First, the first author introduced literature-based knowledge about the field of demonstrators. Second, we

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discussed each demonstrator in the following way. For ensuring a comprehensive understanding of the demonstrator, we reviewed demonstrator purpose and functionality and finally discussed the applied design principles. Thereby, all participants inductively generated the initial code set. For supporting the discussion and for documenting purposes, we used the visual collaboration platform 'miro' (https://miro.com/). Here, all demonstrator cases were presented and participants could add sticky notes with design principles. Additionally, we recorded the audio of the workshop and transcribed it afterwards.

(ii) After the workshop, we conducted part two of the data analysis. The visual results on the collaboration platform, as well as the transcript of the workshop, served as a basis. The first author collated all initial codes into potential themes, reviewed the themes, defined, named and grouped themes and finally produced the analysis report with theme descriptions, examples and quotes. To ensure inter-subjectivity, the report has been discussed with one workshop participant in detail. The themes were iteratively restructured and renamed until arriving at consensus. The final report has been sent to all workshop participants. Minor changes were applied until arriving at consensus.

3. Results

The proposed typology assists in categorising and understanding 13 key design principles, themed in demonstrator-specific goals (see Figure 3). The typology was built from three perspectives: first, in terms of the communication goal (see Table 1), second, in terms of visitor engagement goals (attraction, initial engagement, deep engagement) (see Tables 2–4) and third, in terms of resource-related goals (low effort in development and operation) (see Tables 5 and 6).

4. Discussion

Demonstrators are powerful artefacts for communicating science and technology. However, there is a lack of knowledge about how to efficiently design

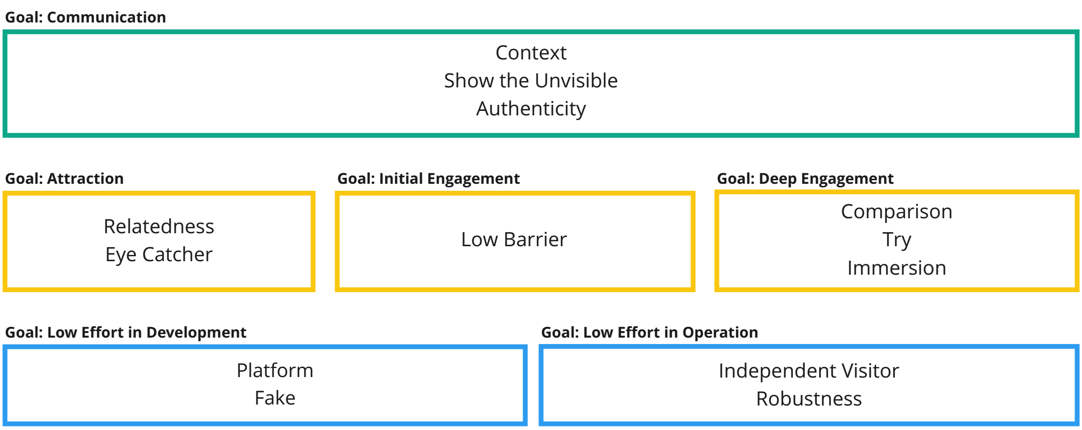

Figure 3. Thirteen Design Principles are categorised into goal-related themes, one relating to communication (green), three relating to visitor engagement (yellow) and two relating to resources (blue).

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Table 1. Design principles related to the communication goal of the demonstrator

Context	Some demonstrators are designed to provide context by embedding the technology or application into a realistic and detailed use case. This can enhance peoples' understanding of the communicated technology. Context can also be applied in a way to make an application more detailed and realistic. This can make it appear like a market-ready product – although it is not. This principle relates to relatedness, immersion and fake	Example: The demonstrator 'Miro' is a robot-assisted surgical system that demonstrates, tests and supports research in the field. Visitors, experts and lay people, can sit at a control console and manipulate robot-assisted medical organ traps, in principle just as a real surgeon would do. It has a high level of detail and 'realness'
Show the invisible	We identified the design principle show the invisible, which uses light or sound effects to show otherwise invisible technology or phenomena. This principle is also used to direct peoples' attention to crucial parts of the demonstrator. There are many ways to apply such effects, depending on communication aim. Taking the modality light as an example, it can range from backlit surfaces to contours or point light, all of them possibly animated or with changing colours. This principle also relates to eye-catcher	Example: The demonstrator 'Convoy' aims at demonstrating the role of communication between autonomous vehicles in a convoy to the public. Visitors can choose between different communication modes, which have an influence on the driving behaviour of the vehicles. Additionally, light bands around the vehicles make the communication between the vehicles visible to support the demonstrator message
Authenticity	The authenticity principle describes the design approach to present authentic and unfiltered science and technology, such as code, circuit boards or other deeper information. Some aspects of this principle can be regarded as contrary to fake	Example: The demonstrator 'Dynamic Power Adaptation' aims at demonstrating dynamic power adaptation of chips, which experts or an interested public can experience by using gestures. The complex structure of the chip, as well as code is visible, which allows an authentic view of the underlying work

demonstrators that effectively communicate to stakeholders with a different knowledge base. Identifying design principles of demonstrators will facilitate researchers with important design knowledge in the concept phase of demonstrator development to exploit the demonstrators potential of a communicating artefact. In this study, we qualitatively analysed 28 interactive demonstrator cases and identified 13 key design principles, which contribute to goals relating to communication, visitor engagement and resource efficiency. Those principles have been derived from and are therefore valid for demonstrators from the fields of robotics and Internet of Things. This study confirmed that the demonstrator is an artefact with both prototype *and* science exhibit characteristics, since we found that most design principles can be supported by – or are related to – literature in the

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Table 2. Design principles related to the goal of attracting visitors

Relatedness	We observed, that some demonstrators are designed to relate to the target group's prior knowledge, interests or everyday life. We assume that this makes people feel personally addressed or curious to invest time and cognitive resources to engage with the demonstrator. Thus, it attracts people to engage with it	Examples: 'Intusi' aims to demonstrate a novel excavator control concept to future users and potential business partners. Details, such as a cup holder, are crucial to the visiting excavator drivers, in order for them to relate to this futuristic concept. The 'Surfing Demonstrator' aims to communicate a potential future application of the tactile internet to teenagers and young adults. To promote engagement, it playfully illustrates an application for the trendy sport surfing
Eye-catcher	We identified the design principle eye-catcher to attract peoples' attention to the demonstrator. This can be achieved through upscaling, size, light, sound, novelty, context or fascinating phenomena	Example: The demonstrator 'Spot' aims at demonstrating a data glove to potential customers, partners and investors. The demonstrator illustrates gesture-based control of the dog-like robot dog, which serves as eye-catcher

Table 3. Design principles related to the goal of initially engaging visitors

Low barrier	We observed demonstrators with a continuum from low barrier to high barrier entry-points. To initially engage people, some demonstrators are designed to provide cues as how to interact. Often these affordances use game characteristics to playfully invite the individual to engage, while others provide the individual a simple task to approach. We noticed that high-barrier entry-points are often characterised by putting on special clothes or devices, which could, in turn, lead to a more immersive experience (see immersion). The two principles thus are contradictory	Example: 'Connected Autonomous Cars' demonstrates next-generation communication concepts with miniature cars, that drive autonomously on a track with an intersection – without collisions. The car design resembles toy cars, which communicates an affordance to interact. Indeed, people were able to interfere and stop cars. We believe that the interaction cue would be absent if the cars would be designed to be less robust and toy-like, but instead, more abstract or futuristic

fields of museum and prototype research. We further notice an ambiguity for some principles. Each, immersion and low-barrier, fake and authenticity, have some contradictory aspects. We elaborate on those aspects in the following sections.

4.1. Museum research

Literature in Museum Research supports the principle context, since situating scientific ideas in real-world contexts and showing how science connects to people,

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Table 4. Design principles related to the goal of deeply engaging visitors

Comparison	To achieve prolonged and deep visitor engagement, we found the design principle of comparing the to-be-communicated technology to other technologies. This allows people to experiment and compare certain system attributes within a technology at their own pace	Example: 'Fast-vpn Latency' is about customers or users experiencing latency – more precisely that IT security does not necessarily have a strong negative impact on latency. It is demonstrated through a racing game, which can be operated by steering wheel. People were able to turn encryption on and off and experience latency-changes in both modes
Try	We observed the design principle try, relating to demonstrators, that aim to communicate their technology as a (soon) market-ready product. People can try out the product and experience it first-hand. Additionally, some demonstrators provide additional context to support understanding and immersion into the use case. If the original application cannot be provided, some demonstrators still provide product experience, for example, through showing down scaled models or faking	Example: The 'FingerTac with VR Evaluation Environment' is a wearable tactile thimble. Other researchers can experience this wearable device first-hand. The demonstrator provides an abstract use case of placing a globe in a virtual environment
Immersion	We observed that demonstrators apply the design principle of immersion, which we frame as a high level of interaction to enable individuals to be fully absorbed in an experience. Immersive demonstrator design involves the use of virtual or augmented reality, embodied interactions or a high level of context. However, we noticed two risks. First, for some immersive demonstrators, individuals need to invest time to start engaging (e.g., when putting on special clothes), which hinders initial engagement. Second, we observed that some demonstrators need a protagonist to start demonstrating in the first place. Without a person engaging with the demonstrator, the demonstrator is not functional, which can be risky, if no person volunteers to engage. This relates to eye-catcher and low-barrier	Examples: The 'Surfing Demonstrator' is an example of providing an immersive experience without forming a barrier. Lay people step on a surfboard imitation and through optical motion tracking, they can operate their real-time avatar surfing through a wave on a big screen in front of them. The demonstrator 'Cleaning Cobots' is another example of an immersive demonstrator. Other researchers or lay people wear VR glasses and controller and clean up a virtual environment. The remote cobot receives the cleaning task and puts the objects into specific boxes

society or the environment enables visitors to connect new information to prior knowledge and experiences (Gilbert & Stocklmayer 2001; Allen & Gutwill 2004). Regarding principle relatedness, learning research suggests that people need to identify themselves with science topics to learn science effectively (Brickhouse,

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Table 5. Design principles related to the goal of saving resources during development

Platform	We observed the principle platform to be a way to save resources during demonstrator development. Building the demonstrator as modular platform (or testbed) and only swap specific elements in the system allows fast and iterative testing and demonstrating	Example: The demonstrator 'Miro' is a modular tele-surgery system for minimally invasive medical procedures. It has operated since 10 years, is constantly in use for research purposes and is used for demonstration purposes to the lay public 1–4 times a month. In our view, 'Miro' applies well the platform principle, which results in its high efficiency
Fake	We observed the design principle fake on various levels. First, imitating the core demonstrator technology, second, faking context-related demo parts and third, fake feasibility of products. Although, the term 'fake' has a negative connotation, we observed this principle as an approach to obtain a demonstrator in an efficient way	Example: The demonstrator 'Lyne Suit' aims to demonstrate a specific future application in a realistic market-ready product-like way, although the technology has not been that far developed yet. The product, a soft exoskeleton, indeed was well designed and showed a high degree of detail. However, an expert audience was disappointed after experiencing the demonstrator's functionality

Table 6. Design principles related to the goal of saving resources during operation

Independent visitor	We identified that with some demonstrators, people could engage independently without any guidance from a supervisor. Designing a demonstrator for autonomous operation has the advantage of reducing resources on site (no supervisor). However, developing such demonstrators requires a certain level of robustness, which might require more resources during development	Example: 'Low-Latency Robotic Airhockey' is a demonstrator, communicating latency differences between the communication standards 3G, 4G and 5G. Lay people could engage with this self-explainable air hockey set by themselves
Robustness	We observed that operating a demonstrator without spending too many resources requires the demonstrator to be robust. This applies to both the actual use but also in terms of setting-up and dismantling. At best, both can be done without engaging any expert knowledge or skills. However, developing robust demonstrators might take up more resources during development	Example: The 'Surfing Demonstrator' is designed in a way that it can operate without any supervisor. Additionally, setup and dismantling can be done in a very short time by any trained person

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Lowery & Schultz 2000; Archer *et al.* 2012). Hence effective science exhibits should adapt to the target group's activities, topics and aesthetics. The literature also supports the eye-catcher principle, providing evidence that large, sound-emitting or moving exhibits attract the attention of visitors to a greater degree (Melton 1972; Peart 1984; Bitgood, Patterson & Benefield 1988) and that technological novelty promotes visitor attention (Sandifer 2003). However, we believe that this principle bears the risk of visitors perceiving the eye-catcher itself as the main content of the demonstrator even when it is not. The principle low barrier can be confirmed by museum research, since there is evidence that low-pressure settings, the opportunity to observe others and offering playful, clear entry points are conducive for visitors to initially engage with an exhibit (vom Lehn, Heath & Hindmarsh 2001; Meisner *et al.* 2007). Regarding the principle comparison, literature confirms that to promote prolonged visitor engagement, an exhibit should enable open-ended exploration and foster investigation (Sandifer 2003; Gutwill & Dancstep (Née Dancu) 2017) in order for visitors to actively construct knowledge by investigating their own questions, in contrast to placing visitors in the role of passive recipients of information (Hein 2000; Rennie & Johnston 2004).

Regarding the principle immersion, we found three different interpretations of what an immersive exhibit comprises that match our analysis very well: (a) Exhibits that replicate environments and recreate realistic, life-sized settings that place visitors in a certain time, location or situation (immersive context) (Bitgood, Ellingsen & Patterson 1990; Gilbert 2002). (b) Exhibits that enable virtual experiences in simulated worlds (Dede *et al.* 2000) (virtual or augmented reality) and (c) exhibits that allow 'whole body' experiences, where visitors use their body beyond walking or sitting (embodied interactions) (Falk *et al.* 2004). The literature suggests that immersive exhibits attract and engage visitors on a higher level, while they do not necessarily provide better learning experiences (Dancstep *et al.* 2015). This principle would be interesting to explore more deeply in future research.

The principle independent visitor illustrates one main difference between exhibits and demonstrators, since in museum contexts, visitors engage without explainers, while demonstrators are mostly accompanied by explaining scientists. Research on the role of explainers argues that they facilitate the visitor experience while encouraging visitors to engage and to reason about the exhibit (Rodari & Xanthoudaki 2005). However, the quality of facilitation depends heavily on the explainers' preparation and pedagogical knowledge. We recognise the potential of demonstrators to be conversation openers for people with different knowledge backgrounds but are aware of the resource-intensive job of supervising. We are interested in further exploring the effect of this principle on communication aims.

4.2. Prototype research

Some design principles are especially relevant for application-oriented demonstrators, which already communicate a technology application or its technical/market fidelity. Those demonstrators resemble prototypes of a soon-to-be market-ready product and therefore are closely related to the prototyping literature. The principle try relates to the very basic concept of prototyping, which (next to exploration) serves as a tool for communication and evaluation among different stakeholders (Star 2010) by creating shared tacit knowledge (Henderson 1991; Rhinow, Köppen & Meinel 2012). Both the principles context and fake can be

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applied to make an application-oriented demonstrator appear more like a market-ready product and therefore relates to fidelity discussions around prototypes (Virzi *et al.* 1996). High-fidelity products can evoke different reactions (e.g., excitement for product aesthetics) but also expectations (e.g., to functionalities) to a demonstrator. We assume that a product with a high perceived fidelity poses the risk of disappointing visitors, especially experts, after testing. We believe this principle should only be used for certain purposes, such as making future technology tangible for a nonexpert target group. However, we also see ethical concerns, which makes a transparent communication about what has been faked and why crucial.

4.3. Design research

Relating to the principle low barrier, Norman (1998) coined the term affordance, which refers to […] those fundamental properties that determine just how the thing could possibly be used.

It results as a basic requirement in human-centred design to achieve good usability outcomes in human–machine interaction. The principle relatedness can further be promoted by technology acceptance research: The Unified Theory of Acceptance and Use of Technology (UTAUT) model describes 'habit' among seven other factors, which influences the acceptance of a technology (Venkatesh, Thong & Xu 2012). The principle platform refers to modularity as a design concept. It describes the decomposition of a product into components, which facilitates the standardisation of components and increases product variety (Gershenson & Prasad 1997). Modularity further plays an important role in sustainable design from a life cycle perspective (Sonego, Echeveste & Debarba 2018). Adapting this principle to demonstrators can result in the benefit of quickly upgrading, adapting or modifying certain elements, which can promote a vast variety of demonstrators.

We assume that some principles strongly depend on the respective target group, which can in general be split into experts and nonexperts. Taking the principle authenticity as an example, we assume that too much unfiltered or raw technology could be overwhelming and discouraging for a nonexpert target group, while too little authenticity could disappoint an expert target group. However, providing authentic insight into the multifaceted research and development behind housings or interfaces might increase the credibility of research projects and justify research or business funds. It also communicates a more realistic picture of scientific processes. The principle fake also strongly depends on the target group and communication aim. Wizard of Oz prototypes allows a communication of functionalities, applications or experiences that have not been developed yet. It might be a valuable approach as a conversation opener at an early development stage, especially with a nonexpert audience. Those two principles are contradictory and it would be interesting to explore this topic further.

4.4. Limitations

However, the results should be considered with care, since the 28 demonstrator design cases have a narrow scope, both locally and thematically. Approximately 72% of demonstrator cases derive from one research institution (TU Dresden). Furthermore, approximately 48% of demonstrator cases derive from one research

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cluster, based in Dresden. Thematically, the demonstrators are limited to the fields of Internet of Things and Robotics. Hence, the research should be regarded as specific to the local research landscape in Dresden (Germany) and only to the two mentioned thematic areas of technology development. However, this scope allowed a much greater depth of understanding design principles than would have been possible from a broader sample.

4.5. Implications

We suggest the following implications for practice:

(i) Including design knowledge into the scientific process can have an impact on the quantity and quality of created artefacts, such as demonstrators with their multitude of purposes. This should be considered already in research proposals to provide resources for such skills.
(ii) Scientists should be informed about the role of demonstrators, including possible target groups and design principles for them to consciously plan and create demonstrators for their needs.
(iii) Raising awareness for the demonstrator as an important communication tool is crucial also among other stakeholders at scientific institutions, such as decision-makers, communication offices or technology transfer offices.

5. Conclusions

In this article, we present the results of a thematic analysis to identify design principles among 28 demonstrator cases, which we collected through an online survey. The resulting typology consists of 13 design principles, themed in demonstrator-specific goals. The framework gives a comprehensible overview of design principles for technology demonstrators and is able to facilitate research teams with rich design knowledge in the concept phase of demonstrator development. Eventually, the framework supports to exploit the demonstrators full potential of a communicating artefact and to save resources during development and operation. The main insights further indicate that (a) visitor experience and resource efficiency are both important drivers in demonstrator design, (b) the target group (broadly divided into experts and nonexperts) influences the choice and form of design principles and (c) some design principles, such as immersion versus low barrier or fake versus authenticity, are contradictory since they are associated with one goal while degrading another.

The identified design principles provide many opportunities for further research, such as extending the framework to other fields of technology. In the near future, we aim to explore the effect of specific design principles on science communication aspects with nonexperts. This could lead to a more precise and evidence-based knowledge base about the design and experience of demonstrators. To make current and future results even more accessible to demonstrator developers, future work will include the transfer to an open and easily accessible tool.

To conclude, this typology of design principles is an important first step in understanding the conceptual design of scientific demonstrators for communicating technology research and development. More effective communication between different disciplines or nonacademic stakeholders has the potential to facilitate inter- and transdisciplinary cooperation to tackle the challenges of an increasingly complex world and consciously shape the future for the better.

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A. Appendix

A.1. Online survey

Introduction

We want to investigate the role and characteristics of the demonstrator in technology research and development. For this, we need a large number of case studies of technology demonstrators. It would be very helpful if you enter all demonstrators one after the other that you have (co)developed.

General information about the demonstrator

What is the name of the demonstrator?
Which institution/s does the demonstrator belong to?
What was the approximate effort of developing this demonstrator (in person-months)?

Objectives

What is the primary goal or intention of the demonstrator?
Who is the associated target group?
Where is it used/shown?
What other goal or intention is being pursued with the demonstrator?
Who is the associated target group?
Where is it used/shown?

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Design

On what basic concept is the demonstrator (or the interaction with it) based to achieve the goal/s?
What characterises the final demonstrator, and how could/can it be experienced?
Please upload a photo of the demonstrator.
Is more information about the demonstrator available online (e.g., video, website, publication)?

Reflection

To what extent was the goal/s met (or not met) with the demonstrator?
In your view, was the effort involved in developing the demonstrator worthwhile?
What is your assessment based on?
Is there anything else you would like to share with us?
In case we have any questions, feel free to leave us an email address.

A.2. Overview of demonstrators

Tables A1–A4 give an overview of the 28 demonstrator design cases, which have been analysed during the study. The tables comprise of the demonstrator names, originators, objectives, target groups and the identified design principles. The objectives and target groups are direct quotes from the online survey.

Table A1. Condensed overview of demonstrator design cases, part 1

Name and originator	Objective/s	Target group/s	Design principles
(1) IoT-Panorama from Barkhausen Institut gGmbH	"To introduce to the general public what IoT really is and can be. Where IoT can be used in everyday life. Stimulate social discourse about the opportunities and challenges of IoT. To be able to use an interactive installation to enter into a conversation with the visitors (the panorama can otherwise be used independently)" [translated]	"People with an affinity for technology and critical people, young people" [translated]	Relatedness, Context, Show the Unvisible, Context, Low Effort, Independent Visitor, Fake
(2) Connected Autonomous Cars from Deutsche Telekom Chair of Communication	"Visualising the benefits of connected driving, Research in the field: cooperative	"Automotive and telecommunications industry, Politics, Students" [translated]	Relatedness, Context, Eye-Catcher, Low Barrier

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Table A1. Continued

Name and originator	Objective/s	Target group/s	Design principles
Networks, TU Dresden	communication approaches, QoS" [translated]		
(3) UUGL1120 as near-to-eye Evaluation Kit from Fraunhofer Institute for Organic Electronics, Electron Beam and Plasma Technology FEP	"Acquisition of industrial customers/project partners" [translated]	"Industrial customers" [translated]	Try
(4) Miro from German Aerospace Center (DLR)	"The main purpose of the demonstrator is to conduct research with it. Furthermore, a functioning demonstrator makes it possible to check whether certain research goals have been achieved. The third function of the demonstrator is to present research projects to professional and lay audiences" [translated]	"Primarily experts from certain scientific communities" [translated]	Context, Try, Platform
(5) Low-Latency Robotic Airhockey from Barkhausen Institut gGmbH	"To illustrate the difference in latency between 3G, 4G and 5G mobile communications" [translated]	"The general public, especially the technically interested public" [translated]	Low Barrier, Affordance, Independent Visitor
(6) Rock, Paper, Scissors from Chair for Industrial Design Engineering, TU Dresden and CeTI	"Showing the latest developments in textile sensors using a glove for robot control, in addition, communicating future human-robot collaboration and tactile internet" [translated]	"The general public, pupils" [translated]	Relatedness, Low Barrier, Try, Show the Unvisible

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Table A2. Condensed overview of demonstrator design cases, part 2

Name and originator	Objective/s	Target group/s	Design principles
(7) Connected Cars – Convoy from Barkhausen Institut gGmbH	"We want to show how important vehicle communication is for safe driving in autonomous vehicle convoys. We want to show the advantages of driving in a convoy" [translated]	"General public, technically interested people" [translated]	Context, Low Barrier, Comparison, Eye-Catcher, Show the Unvisible, Independent Visitor
(8) Cleaning Cobots from Chair of Software Technology, Chair of Computer Graphics and Visualisation, TU Dresden and CeTI	"Basic demonstrator to which our research results can be applied, Representation of the chair in the field of robotics" [translated]	"Researchers, other CeTI rooms, people interested in technology, pupils" [translated]	Immersion, Low Barrier
(9) INTUSI from Chair for Industrial Design Engineering, TU Dresden and Liebherr Hydraulikbagger AG	"Presentation of a new operating concept for excavators" [translated]	"Users, developers, management" [translated]	Context, Try, Show the Unvisible, Low Barrier, Fake
(10) Feldschwarm 1:6 from Chair for Industrial Design Engineering, TU Dresden	"Presentation/ communication and evaluation of acceptance of the concept [of autonomous field robots for agriculture]" [translated]	"Farmers and people interested in agriculture, visitors" [translated]	Context, Try, Show the Unvisible, Low Barrier, Fake
(11) Spot Demo from Mimetik UG and CeTI	"Presentation of the start-up Mimetik and demonstration of the core product (data glove)" [translated]	"Potential customers, industry partners and investors" [translated]	Relatedness, Try, Eye Catcher, Show the Unvisible
(12) Meshmerize for Drones from Meshmerize GmbH (previously a project of TU Dresden)	"To explain the role and capabilities of mesh networks in dynamic robot use cases, especially in the context of drone applications"	"Industry leaders"	Immersion, Low Barrier, Comparison
(13) Neuromorphic Power Management from Chair of Highly-Parallel VLSI Systems and Neuro-Microelectronics, TU Dresden	"Demonstrate how a neuromorphic multiprocessor system adapts to the ever-changing computational load of simulating pulsed	"Scientists, technically interested laypersons, students" [translated]	Comparison, Transparency

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Table A2. Continued

Name and originator	Objective/s	Target group/s	Design principles
	neural networks, thus saving energy, Provide insight into current research and arouse interest in chip design and neuromorphic systems" [translated]		
(14) Low-Latency Teleoperation from Vodafon Chair for Mobile Communications Systems, TU Dresden	"Demonstration of teleoperation, Difficulties of wireless transmissions to achieve reliable, low-latency transmissions" [translated]	"Professionals (with and without communications background), the general public" [translated]	Low Barrier

Table A3. Condensed overview of demonstrator design cases, part 3

Name and originator	Objective/s	Target group/s	Design principles
(15) EndoMersion from National Center for Tumor Diseases, Dresden and CeTI	"Prototype for immersive camera control during laparoscopic surgery, Development and evaluation of methods for tele-surgery" [translated]	"Surgeons, engineers, psychologists" [translated]	Immersion, Context
(16) Surfdemo 2.0 from Chair for Industrial Design Engineering, TU Dresden and CeTI	"Making the Tactile Internet and one potential application tangible and understandable" [translated]	"The general public, pupils" [translated]	Relatedness, Immersion, Context, Low Barrier, Show the Unvisible, Independent Visitor
(17) Event camera-based object tracking with dynamic power adaption from Chair of Highly-Parallel VLSI-Systems and Neuro-Microelectronics, TU Dresden	"Connect the DVS camera with our neuromorphic chip (SpiNNaker2 prototype), Benefit from the sparsity of camera events, our neuromorphic chip as power as much as possible"	"Experts and interested public"	Transparency
(18) Lyne Suit from Chair for Industrial Design Engineering and 5G Lab Germany, TU Dresden	"The aim was to demonstrate the possibilities of almost real-time data transmission with the help of a wearable demonstrator and to make it tangible. […]	"Professional audience (scientists, tech companies)" [translated]	Relatedness, Immersion, Context, Try, Show the Unvisible, Fake

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Table A3. Continued

Name and originator	Objective/s	Target group/s	Design principles
	Rowing is an example chosen for performance-oriented sports in which there is a high acceptance of using technical aids and sophisticated training plans. The demonstrator also serves as an impetus for a discussion on whether there is a broader use of such systems on humans (such as rehabilitation)" [translated]		
(19) AN.ONGuard from Chair of Privacy and Data Security, TU Dresden	"Educating the population about possibilities for anonymous web surfing in the case of mobile end devices (smart phones)" [translated]	"General population" [translated]	Try
(20) Immersive distributed robotic coworking from Chair of Software Technology, TU Dresden	"To show that the following is possible with the current state of the art: distributed work of robots in Germany, immersion into robot environments via a central immersive (AR) interface, send and receive robot commands from any location, thus coworking in a distributed manner, Human-robot coworking" [translated]	"Students, scientists, teachers" [translated]	Immersion, Eye Catcher, Show the Unvisible

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Table A4. Condensed overview of demonstrator design cases, part 4

Name and originator	Objective/s	Target group/s	Design principles
(21) fastvpn-Latency from Chair of Privacy and Data Security, TU Dresden	"It is about the experience of latency – more precisely that encryption does not necessarily have a strong negative impact on latency" [translated]	"Customers/users" [translated]	Relatedness, Low Barrier, Comparison
(22) Microslicing from Chair of Privacy and Data Security, TU Dresden	"It should be shown how differently trusted (IoT) devices can be sorted into separate trust domains/network with the help of a (semi-automatic) separation of the home network" [translated]	"End users/customers (equipment suppliers, network operators, etc.)" [translated]	Context, Try, Show the Unvisible
(23) Digital Twin from Deutsche Telekom Chair of Communication Networks, TU Dresden	"The aim of the demonstrator is to investigate the alternative interaction methods between operator and machine and to formulate an idea for a remote control" [translated]	"Industrial partner in mechanical engineering, warehousing, etc." [translated]	Immersion, Context, Low Barrier
(24) Practical deployment of network coding for real-time applications in 5G networks from Deutsche Telekom Chair of Communication Networks, TU Dresden	"Show the feasibility of SDN/NFV for 5G applications in general, and video streaming in particular"	"Experts"	Comparison
(25) Robot Collective from Munich Institute of Robotics and Machine Intelligence, TU München	"Demonstration of current research from various fields (primarily Robot Learning)" [translated]	"Experts, laypeople" [translated]	Eye Catcher, Show the Unvisible
(26) FingerTac with VR Evaluation Environment from Institute for Robotics and Mechatronics, German Aerospace Center (DLR)	"The demonstrator consists of two components, each with its own goals, namely the FingerTac and the VR. The aim of the FingerTac: to generate vibration feedback as augmented haptic	"Developers and users of tactile wearables" [translated]	Low Barrier, Try

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Table A4. Continued

Name and originator	Objective/s	Target group/s	Design principles
	feedback at the fingertip so that users can touch and interact with both real and virtual objects" [translated]		
(27) Virtual Pianist from Chair for Industrial Design Engineering, TU Dresden and CeTI	"To illustrate CeTI's vision of the Internet of Skills with the use case of piano playing" [translated]	"Broad public, pupils" [translated]	Context, Try, Eye Catcher
(28) Mister T (Jacket) from Deutsche Telekom Chair of Communication Networks, TU Dresden	"Experiencing technology 5G standard (latency free data transfer) over long distances and the influence of latency on the experience of e.g. transmission of motion data in real time. (Making abstract invisible technology tangible) – inspiration for all that would be possible with the new technology" [translated]	"Visitors of the mobile world congress, visitors interested in technology, experts from the telecommunications/ consumer electronics sector" [translated]	Relatedness, Immersion, Try, Comparison

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