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Beyond the channel: A literature review on ambient displays for learning

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ABSTRACT

The review analyses work in the research field of ambient display with a focus on the use of such displays for situational awareness, feedback and learning. The purpose of the review is to assess the state-of-the-art of the use of ambient displays with an explicit or implicit learning purpose and the possible classification of respective prototypes on the basis of a presented framework. This framework is comprised of theories around the educational concepts of situational awareness and feedback as well as design dimensions of ambient displays. The review sheds light on results of recent empirical studies within this field as well as developed prototypes with a focus on their design and instructional capabilities when providing feedback. The results expose that the explicit use of ambient displays for learning is not a prominent research topic, although implicitly ambient displays are already used to support learning activities fostering situational awareness by exploiting feedback. Overall ambient displays represent a technological concept with great potential for learning and the review facilitates a proper foundation and research questions for further research in this direction – towards ambient learning displays.

1. Introduction

The adjective *ambient* is defined as "relating to the immediate surroundings of something" or "relating to or denoting advertising that makes use of sites or objects other than the established media" (Oxford Dictionaries, 2010), while the noun display is among others defined as "a collection of objects arranged for public viewing", but also as "an electronic device for the visual presentation of data or images" (Oxford Dictionaries, 2010). Following these definitions the compound term *ambient displays* characterises appliances present in the close proximity of mainly visually solicited receivers. The technical term this review is referring to goes beyond this mere linguistic definition, describing a renunciation of human–computer interaction (HCI) paradigms where information is delivered constantly demanding the focus of attention. Looking beyond this unilateral communication channel Wisneski et al. introduced ambient displays as "new approach to interfacing people with online digital information" (Wisneski et al., 1998). Inspired by Weiser's vision of ubiquitous computing (Weiser, 1993) the "information is moved off the screen into the physical environment, manifesting itself as subtle changes in form, movement, sound, colour, smell, temperature, or light" (Wisneski et al., 1998). Instead of demanding attention the approach exploits the human peripheral perception capabilities.

The presented review is analysing and classifying work in the research field of ambient displays with a focus on their use for learning support. With this focus in mind the main perspectives on ambient displays are described and a corresponding classification framework for this review is introduced. The review sheds light on results of recent empirical studies within this field as well as developed prototypes with a focus on their design and instructional capabilities. In doing so the review contributes to a theory development in the field unfolding patterns and connections among the presented empirical studies, their prototypical designs, and instructional components. The review results are intended to fill existing research gaps and facilitate a foundation for further research with a focus on the utilisation of ambient displays in a learning context towards an integrated framework for ambient learning displays.

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1.1. Perspectives and classification framework

The classification framework for this review article is affected by three perspectives: a) informational and interactional design of developed ambient display prototypes, b) stated objectives and empirical effects reported in reviewed articles, and c) deducible instructional characteristics for further research.

The design perspective builds on a conceptual design framework proposed earlier by the authors that defines ambient learning displays and consists of parts dedicated to user and context data acquisition, channelling of information, and delivery of contextualised information framed in a learning process. This information might be delivered addressing the receiver's vision, hearing, haptic, olfaction, or taste utilising ambient information systems. Based on a comparison and discussion of existing ambient information systems by Pousman and Stasko (2006) respective systems can be classified. The four design dimensions information capacity, notification level, representational fidelity, and aesthetic emphasis are thus used within the classification framework to describe the reviewed ambient display prototypes. According to the authors information capacity is determined by the amount of information represented by the system, notification level is the degree of user interruption, representational fidelity describes how the data is encoded, and the last dimension reflects the emphasis put on aesthetics (Pousman & Stasko, 2006).

For a further analysis and classification of the developed ambient display prototypes, more empirical insights are needed. Thus the second perspective is based on an empirical analysis of the reviewed articles in general and the prototypes specifically with a focus on the stated research problems and purposes, which indicate besides the main research questions also the variables of interest, the types of studies, and the used methodologies or evaluation strategies. Lastly, the reported results and findings inform about observations made when deploying the prototypes.

Awareness is one of the key concepts of informal learning support (Syvanen, Beale, Sharples, Ahonen, & Lonsdale, 2005) that can be used as instrument to acquire information relevant (e.g. about tasks, concepts, or the workspace) for the learner within the ubiquitous learning environment (Ogata, 2009). Following Wisneski's view (Wisneski et al., 1998) on ambient displays, who defines ambient displays as embedded in the environment close to the user and presenting information related to the user's current context, awareness can be deduced as a main instructional characteristic of ambient displays. To grasp the application possibilities of ambient displays in learning contexts this concept needs to be further exploited. Therefore the classification framework is accomplished with an instructional perspective considering situational awareness (Endsley, 2000). Endsley defines situational awareness as "the perception of elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future". Following this definition the author presents three levels of situational awareness that can be used for classification, namely perception, comprehension, and projection. Perception is related to situational cues and important or needed information, comprehension relates to how people integrate combined pieces of information and evaluate their relevance, and finally projection relates to how people are able to forecast future events and situations as well as their dynamics. Especially on the higher levels of situational awareness the type and characteristic of feedback given by the ambient displays plays an essential role for their effectiveness, impact, and behavioural change capabilities and thus is another important instructional characteristic that can be deduced. In that sense the classification framework also incorporates the concept of providing (instructional) feedback based on an extensive research review in this area by Mory (2004). While her review is not focused specifically on computer-mediated feedback the general feedback research variables of interest presented are also applicable for studying the interaction between learners and ambient displays. These variables are information content and load referred to as complexity, timing, error analysis, learning outcome, and motivation. Thereby the author differentiates several levels of complexity like simple verification, try-again feedback, or elaborated feedback. The timing of the feedback can be immediate or delayed, while errors can be analysed if at all in a corrective or confirmatory manner. The learning outcome can target again several levels, including declarative knowledge or concept learning and even higher-level outcomes like rule learning, problem solving, cognitive strategies, psychomotor skills, or attitude learning. In addition feedback can have effects on a motivational level, e.g. in relation to self-efficacy and task expectancy, triggered by goal or performance discrepancy, or exposed by causal attributions. Unfortunately the listed theoretical approaches depicting the research variable motivation are not distinct enough and thus impede the intended classifying mapping. Therefore the motivational component has been neglected within the classification framework.

2. Method

The presented review is limited to empirical research linked to or addressing specifically the topic ambient displays. Consequently, non-empirical research has been excluded from the review. Evidence-based conceptual research however is included. The underlying search was conducted utilising the online research repositories of the Association for Computing Machinery (ACM), the publisher Springer, as well as the IEEE Computer Society. The focus on these repositories is reasonable as they cover a sufficiently large number of relevant publications.

Within the ACM Digital Library an advanced search was performed in early June 2010, querying for all articles of type journal, proceeding, or transaction, that had been published since 2000 and matched the author keywords "ambient" and "display". The query revealed 77 results whereof 25 were not appropriate. From the remaining 52 articles 22 were considered as empirical research and thus selected for the review. In Springer's research publication database SpringerLink an advanced search was performed in early September 2010, querying for all articles that matched the full text "ambient display" and had been published between January 2000 and September 2010. The query revealed 117 results whereof 37 were not appropriate. From the remaining 80 articles 21 were considered as empirical research and thus selected for the review. Within the IEEE Computer Society Digital Library an advanced search was performed in late September 2010, querying for all articles included in magazines, transactions, or conference proceedings, that had been published since 2000 and matched the exact phrase "ambient display". The query revealed 100 results whereof 3 were not appropriate. From the remaining 97 articles 10 were considered as empirical research and thus selected for the review.

The selected 53 articles were analysed in two phases. In the first phase each prototype was classified in terms of informational and interactional design. Then each article was examined and summarised depicting the objective as well as the reported results and findings. In the second phase these prototypes were then sorted out and synthesised in the integrated classification framework, regarding the addressed situational awareness level and the instructional feedback provided. Fig. 1 illustrates the classification framework and the process of

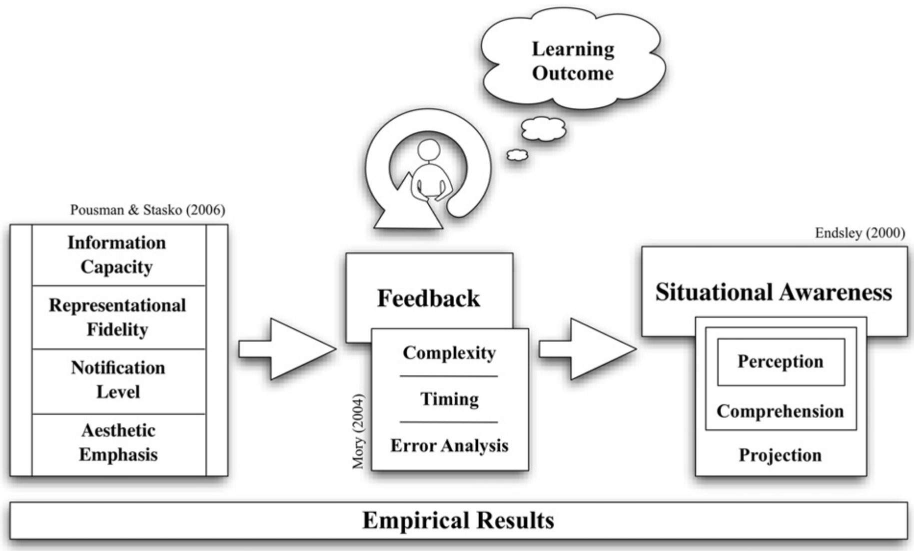

Fig. 1. Classification framework.

classifying prototypes. The situational awareness level and the feedback characteristics are a subjective measure based on Endsley's definition and Mory's description, which depend on the design and objective of each prototype. The classification builds upon Pousman and Stasko's taxonomy of ambient information systems (Pousman & Stasko, 2006) and additionally covers the introduced instructional characteristics. Regarding the ranking on the four design dimensions information capacity and aesthetic emphasis are ranked "Low", "Somewhat Low", "Medium", "Somewhat High", or "High". For aesthetics this is a subjective measure of the emphasis put on it. For information capacity the number of discrete sources of information is used as measurement. Prototypes with single information sources are ranked "Low", with three sources "Medium", and with more than five sources "High". Following Pousman and Stasko's suggestion the prototypes representational fidelity is ranked "Index", "Iconic", or "Symbolic" depending on the abstraction level of the presentation. Similarly the prototypes notification level is ranked "Ignore", "Change blind", "Make aware", "Interrupt", or "Demand attention" depending on the prototype's unobtrusiveness or obtrusiveness.

3. Results

3.1. Informational and interactional design

In total 55 prototypes are presented in the 53 reviewed articles. Table 1 presents these prototypes listed by authors. These prototypes can be classified according to the design dimensions information capacity, notification level, representational fidelity, and aesthetic emphasis

Table 1
Presented prototypes by authors.

Prototypes (Authors/*Name*)					
Altosaar et al. (2006)	*AuraOrb*	Harboe et al. (2008)	*Social TV 2*	Olivier et al. (2006) [a]	*Crossboard, Crossflow*
Bodnar et al. (2004)		Hazlewood et al. (2008)		Otjacques et al. (2006)	*Ambient Workplace*
Bonanni (2006)	e.g. *SmartSink*	Ho-Ching et al. (2003)	e.g. *Positional Ripples*	Palay and Newman, 2009	*SuChef*
Brewer et al. (2007)	*Nimio*	Kim et al. (2010) [a]	*Coralog, Timelog*	Plaue et al. (2004) [b]	*InfoCanvas*
Carter and Mankoff (2005) [a]		Kimura and Nakajima (2008)	*Ambient Lifestyle Feedback*	Reitberger et al. (2007)	
Consolvo and Towle (2005)	*CareNet Display*	Kuznetsov and Paulos (2010) [a]	*UpStream*	Röcker and Magerkurth (2007)	
Consolvo et al. (2004)	*CareNet Display*	Lamberty et al. (2010)		Shinohara et al. (2007)	*Mirai-Tube*
Consolvo, Klasnja, et al. (2008)	*UbiFit Garden*	Mankoff et al. (2003) [a]		Skog et al. (2003)	
Consolvo, Klasnja, et al. (2008) and Consolvo, McDonald, et al. (2008) (2)	*UbiFit*	Meschtscherjakov et al. (2008)		Stasko et al. (2004)	
Dadlani et al. (2009)	*Aurama*	Metaxas et al. (2007)	*Daily Activities Diarist*	Streng et al. (2009) [a]	
Fass et al. (2002)	e.g. *MessyDesk*	Minakuchi et al. (2005)	*AmbientBrowser*	Suganuma et al. (2008)	*uEyes*
Froehlich et al. (2009)	*UbiGreen*	Mirlacher et al. (2009)	*Nabaztag*	Tonder and Wesson (2008)	*AmbiMate*
Fujinami and Kawsar (2008)	*AwareMirror*	Müller et al. (2009)	*ReflectiveSigns*	Tsujita et al. (2008)	*SyncDecor*
Fujinami et al. (2005)	*AwareMirror*	Nakajima et al. (2008)	e.g. *EcoIslands*	Valkanova et al. (2010)	*AmbientNews*
Gustafsson and Gyllenswärd (2005)	*Power Aware Cord*	Obermair et al. (2008)	*perFrames*	Ziola et al. (2007)	*DeskJockey*
Gyllensward et al. (2006)	*Element*	Ojala et al. (2010)	*Ubi-hotspots*		

[a] Authors present two prototypical designs.
[b] Authors present three prototypical designs.

(Pousman & Stasko, 2006). The majority of ambient displays keep the information capacity comparatively low. 30 out of the 55 prototypes possess a low information capacity, e.g. Kuznetsov and Paulos's pervasive display "UpStream" (Kuznetsov & Paulos, 2010) showing the individual and average water consumption. 16 prototypes possess a medium and 9 prototypes a high information capacity. Regarding the notification level most presented prototypes are in line with the neither distracting nor demanding attention characteristic of ambient displays. 39 out of the 55 prototypes simply make users aware, while 11 prototypes implement change blind techniques and 5 prototypes interrupt the user and/or demand attention, e.g. the olfactory message notification system presented by Bodnar, Corbett, & Nekrasovski (2004). The applied representational fidelity is multifaceted and evenly distributed. 13 out of the 55 prototypes make use of indexes, 14 prototypes use an iconic representation, 17 prototypes use symbols, and 11 prototypes a representation form in between, e.g. the attentive user interface "AuraOrb" that uses turn taking techniques (Altosaar, Vertegaal, Sohn, & Cheng, 2006). The emphasis put on aesthetics depicts to which extent a prototype fits in form and function to the environment it is embedded in. Thereby the emphasis increases in the course of the development process, as aesthetics of an early mock-up are usually less important than for the deployed product. 33 out of 55 prototypes put medium emphasis on aesthetics, e.g. the "Nabaztag" used in Mirlacher et al.'s study (Mirlacher, Buchner, Förster, Weiss, & Tscheligi, 2009) comparing visual ambient displays and physical embodied displays. In contrast 7 prototypes put a low emphasis and 15 a high emphasis on aesthetics.

The classification of the reviewed ambient display prototypes enables an examination of the distribution among the four design dimensions. When examining the dimensions independently the prototypes are evenly distributed at representational fidelity and bundled at low information capacity, make aware notification level, as well as medium aesthetic emphasis. Fig. 2 illustrates this distribution and highlights among four others the "Element" prototype by Gyllensward, Gustafsson, & Bang (2006) that corresponds exactly with these characteristics. The authors designed the alternative radiator information display consisting of 35 light bulbs to visualise the invisible energy consumption of radiators at home. The display utilises solely internal and external temperature sensors as source of information. Therefore the amount of information represented by the display and as such the information capacity was ranked as low. The display is designed to balance temperature changes by emitting more or less light. In doing so the display gives instant feedback on user activities that influence the temperature or in other words it makes the user aware about the consequences of his/her actions. The notification level depicting the degree of user interruption was ranked accordingly. The feedback information is encoded in such a way that the amount of light emitted corresponds to the effort needed to balance the changes in temperature. Following Pousman and Stasko's taxonomy (Pousman & Stasko, 2006) this metaphorically information mapping leads to a representational fidelity ranked as iconic. The subjective ranking of the display's aesthetic emphasis proved to be difficult. Although the display is well designed and implemented elegantly, it fails to integrate smoothly into existing environments avoiding additional distraction and novelty effects. Therefore the display's aesthetic emphasis was ranked as medium.

3.2. Objectives and empirical effects

Although most of the reviewed articles state more than one specific research problem and purpose of the article, most of them focus on one with a clear objective in mind. Thereby the majority of studies targets on psychological effects of ambient displays rather than exploring

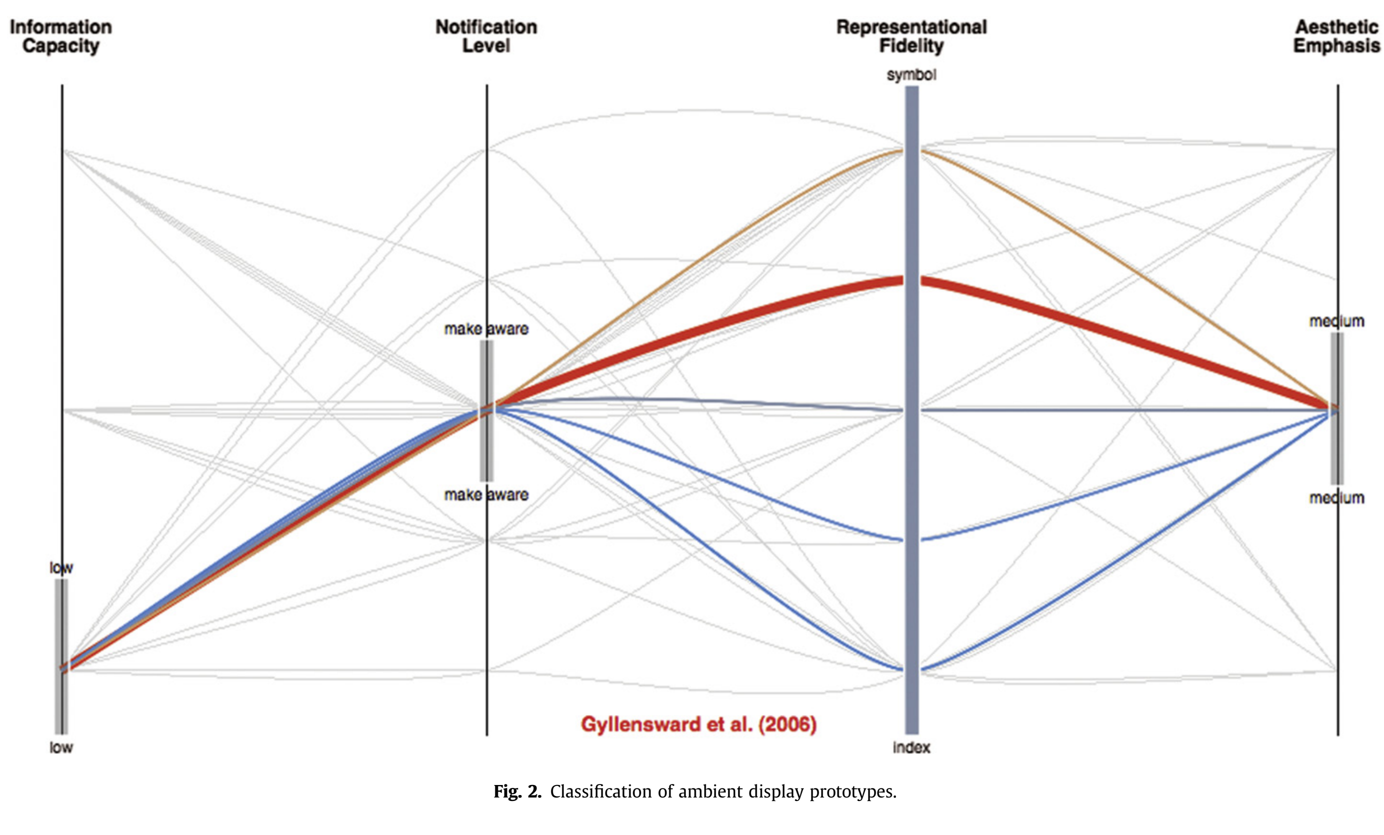

Fig. 2. Classification of ambient display prototypes.

the displays themselves. Across the reviewed articles 18 out of 53 articles stated to raise, enhance, or support awareness (e.g. Metaxas, Metin, Schneider, & Markopoulos, 2007; Tsujita, Tsukada, & Siio, 2008; Valkanova, Moghnieh, Arroyo, & Blat, 2010), covering a spectrum from monitoring personal relevant information (Stasko, Miller, Pousman, Plaue, & Ullah, 2004), over maintaining contact and interaction (Brewer, Williams, & Dourish, 2007), to disseminating important information (Consolvo, Roessler, & Shelton, 2004; Consolvo & Towle, 2005). Going beyond that several articles stated to trigger changes in behaviour (e.g. Bonanni, 2006; Consolvo, Klasnja, et al., 2008; Streng, Stegmann, Huβmann, & Fischer, 2009) underpinned by concepts such as persuasion (e.g. Kim, Hong, & Magerko, 2010; Kuznetsov & Paulos, 2010; Obermair, Reitberger, Meschtscherjakov, Lankes, & Tscheligi, 2008) and motivation (Kimura & Nakajima, 2008; Nakajima et al., 2008; Palay & Newman, 2009). From a more user-oriented perspective several articles stated to give direct feedback (e.g. Froehlich et al., 2009; Gustafsson & Gyllenswärd, 2005; Gyllensward et al., 2006) either by (self)monitoring user actions (e.g. Consolvo, McDonald, et al., 2008; Dadlani, Markopoulos, & Aarts, 2009; Suganuma, Yamanaka, Tokairin, Takahashi, & Shiratori, 2008) or derived from contextual information (e.g. Fujinami, Kawsar, & Nakajima, 2005; Meschtscherjakov, Reitberger, Lankes, & Tscheligi, 2008; Müller, Exeler, Buzeck, & Krüger, 2009). Others stated to provide means for distributed interaction to initiate and escalate communication (Brewer et al., 2007; Harboe et al., 2008; Tsujita et al., 2008) or support cooperation (Otjacques, McCall, & Feltz, 2006; Streng et al., 2009) and collaborative activities, such as sharing work (Lamberty, Froiland, Biatek, & Adams, 2010) or experience (Palay & Newman, 2009). In contrast to the user-oriented perspective some articles disregarded users stating to enrich and complement the environment with ambient displays (e.g. Mirlacher et al., 2009; Röcker & Magerkurth, 2007; Ziola, Kellar, & Inkpen, 2007) mostly by presenting peripheral information (e.g. Fass, Forlizzi, & Pausch, 2002; Minakuchi, Nakamura, & Tanaka, 2005; Shinohara, Tomita, Kihara, & Nakajima, 2007), but also by providing assistance or spatial guidance (Ho-Ching, Mankoff, & Landay, 2003; Meschtscherjakov et al., 2008; Olivier, Gilroy, Cao, Jackson, & Kray, 2006). Lastly the remaining articles stated to focus more on the design of ambient displays by exploring visualisation techniques and modalities (e.g. Bodnar et al., 2004; Fass et al., 2002; Otjacques et al., 2006) mostly adjusting suitable information visualisation concepts (Skog, Ljungblad, & Holmquist, 2003; Tonder & Wesson, 2008), but also examining concepts such as information art (Stasko et al., 2004) or augmented surfaces (Ziola et al., 2007). Others explicitly stated to guide the development and implementation of ambient displays by improving the design process (Carter & Mankoff, 2005; Eisenberg, Eisenberg, Buechley, & Elumeze, 2006; Ferscha, 2007) and developing design guidelines (Pousman & Stasko, 2006; Schmidt & Terrenghi, 2007; Skog et al., 2003) as well as elaborating on evaluation techniques and frameworks (Consolvo & Towle, 2005; Holmquist, 2004; Mankoff et al., 2003) mostly based on prototypical evaluations (e.g. Hazlewood, Connelly, Makice, & Lim, 2008; Ojala et al., 2010; Plaue, Miller, & Stasko, 2004).

Corresponding to the stated research problems and purposes as well as the chosen research methodologies and evaluation strategies the following results and findings are reported within the reviewed articles. The results can be classified into groups dealing with the user experience, functionality, design, and evaluation of ambient displays. In general the user experience of ambient displays is positive. The users received the presented displays well (e.g. Fujinami & Kawsar, 2008; Obermair et al., 2008; Stasko et al., 2004), they were satisfied (Tonder & Wesson, 2008) and showed very good acceptance and interest (Valkanova et al., 2010). The displays were experienced as glanceable (Consolvo, McDonald, et al., 2008; Plaue et al., 2004), intuitive (Gustafsson & Gyllenswärd, 2005), easy to interpret, and understandable (Brewer et al., 2007; Reitberger, Obermair, Ploderer, Meschtscherjakov, & Tscheligi, 2007), although sometimes additional learning effort was needed (Röcker & Magerkurth, 2007). Beside that Mirlacher et al. (2009) note a correlation between likability and the perceived usability. A problem ambient displays have to deal with is that the users interest decreases over time (Shen, Moere, Eades, & Hong, 2008). This novelty effect is hard to overcome (Consolvo, Klasnja, et al., 2008), although long-term studies indicate that the user interest stabilises at the end and even suggest to start the evaluation after this happened (Shen et al., 2008). In terms of user distraction Bodnar et al. (2004) verify that the disruptiveness and effectiveness of notifications varies with the notification modality. Especially notification sounds seem to work well in peripheral settings (Ho-Ching et al., 2003). Additionally ambient displays are experienced as unobtrusive or not distracting (e.g. Minakuchi et al., 2005; Obermair et al., 2008). Across the reviewed studies users also indicated that they would like ambient displays to offer more detailed information (Froehlich et al., 2009; Reitberger et al., 2007) and more interaction possibilities (Stasko et al., 2004). One solution to improve the usefulness of ambient displays might be to allow users to manipulate and offer the possibility to add data (Consolvo, McDonald, et al., 2008).

Concerning functionality the ambient displays were at first glance accepted for presenting information (Fujinami et al., 2005; Mirlacher et al., 2009). The evaluated ambient displays were able to provide awareness (e.g. Brewer et al., 2007; Lamberty et al., 2010; Metaxas et al., 2007) and to increase or raise awareness effectively (Carter & Mankoff, 2005; Consolvo, Klasnja, et al., 2008; Harboe et al., 2008), especially the awareness of information and presence. Furthermore the results of Consolvo et al. (2004) suggest that ambient displays are an effective tool for sharing information, even reducing distraction significantly (Röcker & Magerkurth, 2007). The displays were experienced as intriguing (Gustafsson & Gyllenswärd, 2005; Gyllensward et al., 2006) and thus engaging and motivating (Consolvo, McDonald, et al., 2008; Kim et al., 2010; Kuznetsov & Paulos, 2010). These characteristics positively affected the ability to influence and eventually change user behaviour (Consolvo, Klasnja, et al., 2008; Palay & Newman, 2009). There are different approaches to achieve that objective, e.g. Nakajima et al. (2008) note that keep showing the explicit goal until it is reached is especially effective to permanently change behaviour, while Bonanni (2006) states that an increased sensory feedback is able to motivate behaviour change almost instantly. Finally the ability to give feedback was also valuable and engaging (Froehlich et al., 2009) getting even more efficient on the long-term (Kuznetsov & Paulos, 2010). Thereby instant feedback is not annoying or intrusive (Bonanni, 2006) and metaphoric visualisations have the potential to communicate feedback in a subtler and playful way (Streng et al., 2009).

3.3. *Instructional characteristics and classification*

The explicit use of ambient display prototypes for learning is not a prominent subject of research across the reviewed articles. 4 out of the 53 articles are explicitly concerned with learning and/or education. Generic design principles for educational artefacts in ubiquitous computing are presented by Eisenberg et al. (2006) resulting in fundamental themes that should inform the design process, such as curiosity enhancement, control and programmability, as well as aesthetics. The remaining articles describe or make use of prototypes with a learning outcome in mind. One of them is the “AmbientBrowser” prototype that enriches everyday activities with relevant knowledge utilising peripheral information displays (Minakuchi et al., 2005). Another one comes up from the work on group mirrors to support collaborative learning activities examining different feedback presentations presented by Streng et al. (2009). Both prototypes do not go beyond the mediation of declarative knowledge, addressing cognitive processes like remembering and understanding. A prototype that goes beyond is presented by Lamberty et al. (2010). The article focuses on peripheral displays in educational settings and comes up with a prototype that enables students in classrooms to share personally created mathematical artefacts, e.g. quilt blocks to explore symmetry, with the whole class utilising a large public display. In this case the creation of the artefacts involves more complex knowledge and cognitive processes, while the ambient (peripheral) display is solely used to support the students evaluating their own work and the work of others.

Comparatively more prototypes are used implicitly for learning. As presented earlier a high number of prototypes mention and target increased awareness of users about changes in the environment. Considering the definition of situational awareness by Endsley (2000) ambient displays can contribute to different forms of awareness. The targeted situational awareness can either be on the level of perception, comprehension, or even projection. Ambient displays that are by definition embedded in the current context of use and aim to support learning activities of users in context need to be well described according to the level of situational awareness they aim for. In the course of this review respective prototypes have been sorted out and synthesised according to the introduced classification framework. To do so the performed classification with respect to design dimensions and the empirical analysis have been used. Overall 17 out of the 55 presented prototypes within the reviewed articles were included, selected on their individual ability to address a level of situational awareness as well as the provision of usable feedback characteristics. Table 2 presents these prototypes. Thereby each prototype is assigned to one level of situational awareness (perception, comprehension, projection) based on the stated objectives. Within each level the prototypes are listed in alphabetical order given by their authors. For each prototype the table shows the following information: (a) design dimensions classification following Pousman and Stasko's taxonomy (Pousman & Stasko, 2006) taking into account the prototype's information capacity, notification level, representational fidelity, and aesthetic emphasis, (b) feedback characteristics according to Mory's feedback research variables of interest (Mory, 2004) including complexity, timing, and error analysis, (c) intended learning outcome of the prototype also following Mory's consecutive list, and (d) the reported empirical results and findings regarding the prototype's effectiveness.

Derived from the stated objectives 6 out of the 17 selected prototypes are assigned to the perception level mainly stating to raise, enhance, or support awareness (Gustafsson & Gyllenswärd, 2005; Gyllensward et al., 2006; Kuznetsov & Paulos, 2010). 8 of the prototypes are assigned to the comprehension level going beyond mere perception, most of whom stating to trigger changes in behaviour (Bonanni, 2006; Consolvo, Klasnja, et al., 2008; Froehlich et al., 2009) making use of concepts like persuasion (Kim et al., 2010; Obermair et al., 2008) or motivation (Kimura & Nakajima, 2008). The remaining 3 prototypes are assigned to the projection level of situational awareness. What distinguishes these prototypes is the ability to predict future events, like the "Aurama" prototype (Dadlani et al., 2009) that reflects on the user state by monitoring user actions. Some general observations can be noted regarding the classified design dimensions. As for the majority of all prototypes the information capacity of the 17 selected prototypes is comparatively low. An exception is the "CareNet Display" (Consolvo et al., 2004) that uses several types of information including information about meals, activities, mood, and medication. Regarding the notification level most prototypes are residing on a medium level, which is in line with one of the main ambient display characteristics – to make aware in an unobtrusive manner. The allocations for the remaining dimensions are more widespread. The addressed representational fidelity varies among the prototypes, but seems to increase with the situational awareness level which suggests that the more complex and meaningful the information the more abstract it is represented. Kim et al. (2010), Kuznetsov and Paulos (2010), Streng et al. (2009) compare different representational fidelities in their articles reporting that abstract representations are more effective on raising awareness, foster self-regulation, or increase behavioural impact. The emphasis on aesthetic is heavily dependent on the context in which the prototypes are used and thus out-of-scope to derive general conclusions.

Looking at the individual feedback characteristics the complexity is relatively low among the prototypes, although the complexity increases with the situational awareness level from no feedback over simple verification to elaborated feedback, e.g. the "EcoIslands" prototype that is used to make "the participants conscious of the ecological consequences of their choices and activities" (Kimura & Nakajima, 2008). Thus the prototype provides elaborated feedback in the form of contribution charts as well as activity reports and histories. In general the feedback is mostly timed immediately corresponding directly to user actions. Nevertheless some prototypes effectively make use of delayed feedback e.g., to raise awareness on log-term trend changes (Dadlani et al., 2009). The "UbiFit Garden" prototype (Consolvo, McDonald, et al., 2008) even combines immediate feedback as performance indicator with delayed feedback to reward goal achievements. The error analysis also changes with the level of situational awareness from mostly confirmative feedback to mainly corrective feedback. At the same time the intended learning outcomes become more complex ranging from declarative knowledge and concept learning for the prototypes on the level of perception up to rule learning and problem solving on the higher levels.

Considering also the reported empirical results and findings regarding the prototype's effectiveness enables more profound derivatives and inferences with respect to the theoretical framework. Especially reports that reflect the changing effects and consequences when altering the interplay of design dimensions and feedback characteristics are interesting. As in the article of Kuznetsov & Paulos (2010) who present the "Upstream" prototypes varied on the representational fidelity design dimension, the feedback complexity, and the error analysis. Hence the learning outcomes are different. While the prototype variation with indexical representation, no feedback complexity, and confirmatory error analysis responds to the transfer of declarative knowledge, the opposing variation with symbolic representation, simple verification complexity, and corrective error analysis responds to rule learning postulating a simple cause–effect relationship. In their report the authors state that the second variation effectively increased awareness and motivated behavioural change exactly through the chosen form of representation and the kind of feedback given, which provides "a clear, easily perceptible indication of good and/or bad behaviour" (Kuznetsov & Paulos, 2010). As a general conclusion it can be noted that learning outcomes involving higher cognitive process capabilities are most effectively addressed by abstract information representations with at least simple verification feedback incorporating corrective error analysis. In contrast declarative or concept learning also goes with no feedback complexity and simple confirmatory error analysis.

Table 2
Theoretical framework mapping of selected prototypes.

		Prototype	Design Dimensions				Feedback			Learning Outcome	Result
			Information Capacity	Notification Level	Representational Fidelity	Aesthetic Emphasis	Complexity	Timing	Error analysis		
Situational Awareness	Perception	Gustafsson & Gyllenswärd, 2005 > Power-Aware Cord	Low	Make aware	Iconic	High	No feedback	Immediate	Confirmatory	Concept	Intriguing tool to investigate behaviour. Increased awareness
		Gyllensward et al., 2006 > Elements	Low	Make aware	Iconic	Medium	No feedback	Immediate	Confirmatory	Concept	Intriguing tool to present (intangible) information
		Kim et al., 2010 > Timelog	Low	Make aware	Indexical	Medium	No feedback	Immediate	Confirmatory	Declarative	General increased awareness through unobtrusive persuasive medium; Representation less effective to change behaviour (cf. Coralog)
		Kimura & Nakajima, 2008 > Persuasive Art	Low	Make aware	Symbolic	High	Simple verification	Delayed	Corrective	Rule (Relational)	Animated emphatic visualization more pervasive and thus more effective to change behaviour
		Kuznetsov & Paulos, 2010 > Upstream 1	Low	Make aware	Symbolic	Medium	Simple verification	Immediate	Corrective	Rule (Relational)	Increased awareness led to behavioural impact facilitated through perceptual impact of ambient visualization. Numeric visualization less effective.
		Kuznetsov & Paulos, 2010 > Upstream 2	Low	Change blind	Indexical	Medium	No feedback	Immediate	Confirmatory	Declarative	
	Comprehension	Bonanni, 2006 > Hyper-Reality	Low	Make aware	Symbolic	Somewhat high	No feedback/ Simple verification	Immediate	Confirmatory	Concept	Amplifying sensor experience (motivate behaviour change)
		Consolvo, Klasnja, et al., 2008 > UbiFit Garden	Medium	Make aware	Symbolic	Somewhat high	Simple verification	Immediate/ Delayed	Confirmatory	Rule (Procedural)	Positive reinforcement; Effective for raising awareness. Potentially influencing behaviour.
		Froehlich et al., 2009 > UbiGreen	Low	Make aware	Iconic	High	Elaborated	Immediate	Corrective	Rule (Relational)	Increased engagement/encouragement facilitating behaviour change
		Kim et al., 2010 > Coralog	Low	Make aware	Iconic	Medium	Simple verification	Delayed	Corrective	Rule (Relational)	General increased awareness through unobtrusive persuasive medium. Iconic representation more effective (assistive, emotional) to change behaviour.
		Kimura & Nakajima, 2008 > Virtual Aquarium	Low	Make aware	Symbolic	High	Simple verification/ Correct-response	Immediate	Corrective	Rule (Procedural)	Accumulated feedback effective to keep interest/long-term motivation.
		Obermair et al., 2008 > perFrame	Low	Change blind	Symbolic	High	Simple verification	Immediate	Corrective	Rule (Relational)	High persuasion potential (on the short term) influenced by likability of the display
		Streng et al., 2009 > Group Mirror 1	Low	Make aware	Indexical	Medium	Simple verification	Immediate	Corrective	Rule (Relational)	Strong effect of representation on self-regulation; subtle and playful feedback communication through metaphoric visualization
		Streng et al., 2009 > Group Mirror 2	Low	Make aware	Symbolic	Medium	Simple verification	Immediate	Corrective	Rule (Relational)	
	Projection	Consolvo et al., 2004 > CareNet Display	High	Change blind	Iconic	Medium	Elaborated	Delayed	Corrective	Problem-solving	Increased level of awareness. Effective tool for information sharing task.
		Dadlani et al., 2009 > Aurama	Low	Make aware	Symbolic	High	Simple verification	Delayed	Corrective	Problem-solving	Raised awareness on long-term trend changes
		Kimura & Nakajima, 2008 > EcoIslands	Somewhat low	Make aware	Symbolic	Somewhat high	Elaborated	Immediate	Corrective	Rule (Relational)	Changed attitude (increased consciousness); effective use of social facilitation and conforming behaviour

4. Discussion and conclusion

The articles reviewed and the presented prototypes therein have been analysed and classified based on the introduced classification framework depicting the use of ambient displays for learning. In doing so this specific research field has been examined and summarised, covering design dimensions and characteristics as well as empirical statements and results. The classification of ambient display prototypes according to the introduced design dimensions showed that the majority of prototypes handle only a low capacity of information, are reluctant when it comes to the level of notification by just making aware, utilise all available representational means from indexes to symbols, and put a medium emphasis on aesthetics. Across the reviewed articles all presented prototypes could be described with and classified within the used taxonomy. This illustrates that the taxonomy is already well elaborated and does meet the requirements of an integrated framework for ambient learning displays. With informational and interactional design aspects in mind several research opportunities can be deduced. Especially the influence of the used interaction paradigm on learning and the motivation to learn has not been investigated. Also the relation to the cognitive processes of learning and the role of changing interaction modalities accordingly lacks in-depth research. Connected to that but more an instructional question is the underutilisation of the displays' ability to move between the users' periphery and focus of attention. One assumption when looking at the prototypical designs could be that the more superior the addressed cognitive process, the farther away the displays should be located from the focus of attention. Arguably also the opposite can be assumed, so further research is needed. This is also applicable for the discussed informational aspects, where it can be questioned why only non-critical information should be presented and what the implications are when taking the display out of its context.

The empirical analysis of the reviewed articles highlighted a plethora of objectives stated as well as results and findings reported. The majority of articles are targeted on research about basic psychological effects of ambient displays. To realise the vision of ambient learning displays it is important to go beyond the mere goal to support awareness. Much more effort needs to be put into research on concepts like persuasion, motivation, feedback, and behaviour change to lay the foundation for learning processes supported by ambient displays. Several papers focus on evaluation of the displays design without evaluating learning effects explicitly. Therefore a stronger focus on learning effectiveness would be desirable and presents a research gap that needs to be filled towards ambient learning displays. The results and findings reported indicate a positive user experience and the confidence that ambient displays are suitable to present information. The major issues here are again related to long-term deployments, where novelty effects and a decreasing user interest need to be overcome. In general the presented functionalities the ambient displays provided after all is in line with the earlier stated objectives. Remarkably the term learning is not mentioned across the reviewed articles in this context. At least the terms "giving feedback" and "changing behaviour" made it into the list of functionalities provided, though without providing a suitable evaluation framework. Beside the user experience and functionality several design guidelines (also in an educational context) and principles as well as difficulties are reported.

Inspecting the use of ambient displays for learning revealed that only a minority of articles explicitly use ambient displays for learning, many more address learning implicitly by raising, enhancing, or supporting awareness, changing behaviour, giving feedback, providing assistance and guidance, or just by presenting information. More effort needs to be put into research in this direction, as this is clearly underrepresented across the reviewed articles. At least some work has been done on the design and implementation of respective prototypes, while more work is needed on the evaluation of these prototypes in a learning context. However, this is in line with the authors' expectations of this specific research field and justifies at the same time this review, intended to foster a foundation for further research on ambient displays for learning. The mapping of the corresponding prototypes with the introduced classification framework led to first general design implications, taking into account the instructional characteristics considering concepts like situational awareness and feedback. Although the framework as it is proved to be suitable to draw conclusions on the effectiveness of prototypical variations in a learning context, several research gaps and shortcomings have been revealed. It is questionable if the type of instructional feedback specified is sufficient to cope with the changed handling of information and interaction modalities offered by pervasive technologies such as ambient displays. Other types of feedback might be more efficient, e.g. combining or tweaking defined feedback characteristics. Especially the effect of location-based or contextualised feedback is a yet unexplored research direction in the feedback literature for which ambient learning displays can play an important role in the future. The contextualisation component is not mapped and explored sufficiently within the framework, although the correlation of the context, the display's effectiveness, and the chosen design is obvious.

After all ambient displays can be designed and implemented to successfully fulfil a given purpose, possibly also for learning. Once implemented the known long-term effects as well as the contextual factors that influence the display's efficiency need further investigation. In the dawning age of ubiquitous computing ambient displays represent a technological concept with great potential for learning. Towards ambient learning displays still some work needs to be done, wherein this review can be taken as basis and inspiration to go beyond.

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