FireFlies2: Interactive Tangible Pixels to enable Distributed Cognition in Classroom Technologies

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Figure 1. FireFlies2 consists out of an individual light-object per child and an (tablet) app for the teacher. Pupils rotate the cap of a light-object to change the top colour. The teacher changes the bottom colour via the app: one light-object at a time, or all at once.

ABSTRACT
Continuous developments in the field of Human Computer Interaction (HCI) are resulting in an omnipresence of digital technologies in our everyday lives, which is also visible in the presence of supportive technologies in education. These technologies, e.g. tablets and computers, usually require focused attention to be operated, which hinders teachers from appropriating them while teaching. Peripheral interactive systems, which do not require focused attention, could play a role in relieving teachers' cognitive load, such that mental resources are freed to focus on other teaching tasks. This paper presents an exploratory study on enabling such cognitive offloading through peripheral interaction in the classroom. We present the design and a seven-week field deployment of FireFlies2 interactive tangible pixels which are distributed over the classroom. Our findings show that FireFlies2 supported cognitive processes of teachers and pupils in a number of scenarios.

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INTRODUCTION
Teachers in primary education need to perform multiple activities simultaneously, such as keeping track of children's progress, providing group- and individual instructions and managing the time schedule, often referred to as *classroom orchestration* [32]. Teachers are more and more expected to adapt their instructions to individual pupil's abilities and needs [9]. At the same time, they need to stimulate (social) interaction between pupils (and teachers). This motivates information retention [21] and deep learning, where pupils understand rather than recite the knowledge. All in all, teachers have busy routines [4] which are likely to only get busier in the future.

Various digital technologies are being used in, and developed for, education, mainly to provide a variety of exercises and methods (e.g. adaptive learning materials [25], online courses and peer tutoring [28]), to support administrative tasks of the teacher (e.g. to track attendance [14]), or to promote awareness and reflection through learning analytics [33]. These educational applications are usually operated through graphical user interfaces (GUIs) on smartboards, laptops or tablet computers; interactions which typically rely on repeated focused attention. The use of such classroom technologies during regular teaching tasks can therefore add additional cognitive load to teachers' busy everyday routines.

To minimise attention demand, earlier research has explored the concept of *ambient displays* [10] or *peripheral interaction* [7, 16] in the design of novel classroom technologies. Similar to the way we are aware of everyday information, such as the weather and the time of day, without consciously thinking about it, these designs intend to seamlessly blend into existing routines, requiring minimal mental effort to be used. They have shown to be particularly valuable when supporting teacher's secondary tasks [6, 10]. For example, making relevant information about individual pupils easily accessible as part of the classroom's physical environment (e.g. information about their progress [2, 3], whether they have questions [2], or if it is their turn [5]). When using these designs, teachers no longer have to remember which child already had their turn or who has a question, effectively relieving them from the corresponding mental effort. Such use of the environment and artefacts is also referred to as *distributed* or *situated cognition* [11, 17, 19, 29]. Both teachers and pupils might benefit from assistive technologies that are seamlessly integrated in classroom routines. The ability to distribute cognition could allow for this integration and, in turn, open up possibilities to increase the quality of education.

Prior work by Bakker et. al. [5] on an interactive classroom system presented multiple aspects that indicate positive effects of distributed cognition. Their system, called FireFlies, consisted out of a wireless and tangible light-object for each pupil and a teacher-tool to set the light-colours of those objects. These light-objects allowed for quick and, most of all, silent communication on individual and classroom level (e.g. to indicate who is given a turn, or that pupils are expected to work independently). Bakker et. al. [5] report that, because each pupil had their own tangible light-object, they seemed more aware of classroom rules which were indicated via the light-objects. Additionally, as the *light-objects* retained their colour, all light-objects together became a distributed display (e.g. reminding the teacher of who already had their turn). Similar to findings by Alavi et. al. [2], who explored one-direction communication through distributed light-objects, the presented information is locally visualized and can store information the teacher or pupils no longer need to remember. The work presented in this paper explores a redesign of the FireFlies system, aimed at further enabling such distributed cognition [18].

In this paper, we investigate how presenting low resolution information on a tangible display that is distributed over the classroom can support teachers' distributed cognition during their busy everyday routines. We developed a dedicated open-ended information system, called FireFlies2 (Figures 1 and 2), which consists of a tablet interface and distributed light-objects. The system enables a teacher to communicate with pupils by setting the lower half of their light-objects on specific colours remotely using a tablet interface. In turn, pupils can set the colour of the top half on specific colours. For example, a light-object with a green bottom and a blue top could indicate a compliment given by the teacher and the pupil having a question. We hypothesise that teachers can use this system to offload relevant information they normally would have to remember. We hereby aim to lower their cognitive load, freeing up resources for their primary task of teaching. Additionally, FireFlies2 is envisioned to have an effect on the routines and relationships in the classroom as a whole. We present a qualitative user study in which four part-time primary school teachers and 52 pupils aged 6-8 used the system for seven weeks. We conclude the paper with a discussion of, and possible future directions for, distributed cognition provided by distribution of information over interactive tangible pixels.

THEORETICAL BACKGROUND

The work presented in this paper builds on distributed cognition, ambient displays and peripheral interaction. We briefly introduce these theories in this section.

Distributed Cognition

Clark and Chalmers [12] proposed a theory of the extended mind, in which the environment plays an active role in driving cognitive processes. Similarly, Hutchins [18] argues that cognition is embodied and extends into the world through objects and devices. In cognitive science, this is referred to as distributed cognition [18, 29], situated cognition [11] or extended cognition [12]; a theoretical framework to investigate the coordination between people, artefacts and environments [17].

Our cognition can be distributed, situated or shared, amongst multiple persons or artefacts [29]. It is argued that physical artefacts in the environment can be "picked up, analysed and processed by perceptual systems alone" [35], without the need for retrieving knowledge from memory. We see many examples of the use of such artefacts in everyday life, which help us in everyday thinking and reasoning. For example, one might place a post-it note with the text 'take out the trash' on the living room door to not forget this task. This use of these artefacts and/or our surroundings enables individuals to extend their cognitive resources [29]. When the surroundings are used effectively, such cognitive offloading reduces time and memory demands of the tasks at hand, increasing reliability and amount of tasks possible at that given moment [17].

This research aims to utilise this extension of cognition to convert current internal cognitive tasks into distributed cognitive tasks to free up cognition to be utilised for other tasks of teachers in a primary school setting.

Peripheral interaction

The design used in the study presented in this paper, FireFlies2, borrows from theories of peripheral interaction

[6, 13], which emphasises that both perception of information and interaction with digital systems might shift between the focus and periphery of attention. This type of Human-Computer Interaction (HCI) is grounded in the observation that in everyday life, people can easily divide their attention over various activities [6, 34]. For example, we can be aware of how crowded it is in our surroundings without actively looking around. Similar directions have been explored under the terms calm technology [34], technology that shifts between our focus and periphery of attention such that it can be used without cognitively being overburdened by it, and ambient displays [22], which present relevant but non-crucial information in a subtle manner. With the aims of supporting teachers by lowering the cognitive load required for everyday activities, this paper explores the combination of distributed cognition and peripheral interaction.

RELATED WORK

Distributed cognition theory has been mainly applied in HCI as a framework to analyse current human computer interactions or collaborative processes. For example, it has been used to analyse the use of physical index cards (post-it-like cards used for capturing stories or tasks) in programming teams [31]; to study the approach students take in solving assignments to improve teaching methods [20]; and to study the facilitation of reuse of shared digital artefacts (data) during collaborative analytics [27]. Although some of these related studies provide design implications [27], only few related studies are known to the authors which present interaction designs based on the principles of distributed cognition. Time Machine [1], for example, is a tangible, auditory and ambient display that stacks marbles as representation of time, creating both auditory feedback and an ambient representation of time spent per task. Time Machine thereby intends to aid memory and reduce cognitive load by providing a tangible representative for time management. Code Bits [15] aims to improve computational thinking skills of students by providing tangibility and spatial overview. It uses a paper based toolkit in combination with a mobile application to convert the paper code. The named designs aim to provide principles of distributed or situated cognition in a single object or set, where we aim to distribute cognition over multiple individual devices, making direct use of the spatial environment.

Previous work on classroom technologies or classroom orchestration have used distribution of (peripheral) information to aid the teachers' everyday tasks. Balaam et al. [8], for example, developed a light-object that indicates the emotional state of pupils and provides an overview of this information to the teacher on a tablet. Alavi et al. [2] designed tangible light-objects, called Lanterns, that indicate whether students have a question and how long they have been waiting for help. These Lanterns form a tangible distributed display, which enables other students to act upon the visible distributed information, hereby improving their perception of other's progress. Work on computer-supported collaborative learning (CSCL) has shown to support awareness of and reflection on learning [33]. For example, MTFeedback by Martinez-Maldonado et. al. [24] generates automatic notifications for the teacher based on group collaborative tasks to direct teachers attention more effectively. Differently, this paper aims to provide information more distributed within the classroom itself and regardless of individual or collaborative work. Similarly, related work on ambient displays [22] in the classroom explored the display of relevant information in the teachers' periphery of attention. Lernanto [3], for example, is an ambient display that subtly informs teachers of individual student's progress. Börner et al. [10] present a literature review of research into ambient displays for learning. Most of these reviewed ambient displays mainly aimed at raising, enhancing or supporting awareness of additional information collected, such as the individual average water consumption or physical activity level. These displays introduce additional information, potentially increasing the user's cognitive load. To provide the teacher with a lower cognitive load, we aim to use the principles of distributed cognition on information currently retrieved and used within the classroom.

The research presented in this paper aims to utilize the tangible distribution of knowledge as partly applied in the addressed previous work. Rather than initializing new action possibilities or new ways of working, the presented works takes existing knowledge from the target environment, to replace current ways of working. We aim to investigate the distribution of cognition on current workload and tasks at hand.

FIREFLIES2 RE-DESIGN

This research aims to utilise distribution of cognition over interactive tangible pixels, to convert teacher's current internal cognitive tasks into distributed cognitive tasks to free up mental resources. We envision this by displaying relevant information (e.g. compliments or warnings from the teacher, a pupil having a question), on distributed tangible artefacts. As a potential result, teachers no longer have to remember this information and have more mental effort left for their primary teaching task. The aforementioned prior design by Bakker et. al. [5], called FireFlies, consisted out of individual light-objects for each pupil and a teacher-tool. These individual light-objects could store and visualise basic information originating from the teacher. Building further on the original FireFlies design, this works presents a redesign, called FireFlies2, to investigate distribution of cognition in a classroom setting.

Similar to the original, FireFlies2 consists out of two types of devices: several light-objects and a tablet for the teacher (Figure 1). Where the light-objects of the original FireFlies design could be set to one colour at once, the FireFlies2 light-objects consist of two segments to allow for more elaborate use of the artefacts in pupils' cognitive reasoning. Similar to FireFlies, the colour of the bottom part of each light-object is determined remotely by the teacher using the tablet.

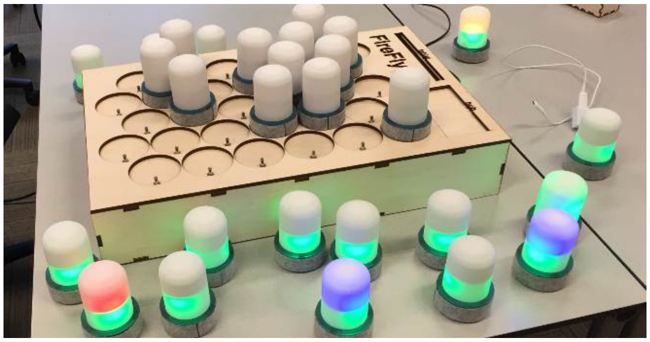

Figure 2. The light-objects (without the pupils' name-stickers) and their docking station. Each light-object contains a microcontroller, receiving instructions from a (constant powered) microcontroller handling communication from tablet to light-objects.

Different from the original, the colours of the top parts of the FireFlies2 light-objects are set locally by the pupils themselves. This can be achieved by rotating the artefact (Figure 3). This design change enables studying the effects of individual distribution of cognition on a group, in this case the pupils and teacher. The light-objects (Figure 2) are semi-transparent 3D printed shells placed on a sturdy base, and contain four Light-Emitting Diodes (LEDs). The objects are larger compared to the original design. This was done to increase visibility of the lights and their displayed colour, especially given the two light-segments.

Furthermore, the redesign replaced the physical teacher tool with a tablet with a dedicatedly designed app. This was done to enable quick and more dynamic manipulation of the colours of the light-objects compared to the tangible tool of the original FireFlies. The teacher application (Figure 4) allows for changing the colour of individual light-objects. The teacher can 'paint' light-objects by selecting a colour and subsequently selecting a pupil's name (Figure 3). Alternatively, selecting "All" will apply the selected colour to all light-objects. Two pupil overviews are available, one in alphabetic order and one ordered by table layout.

Identical to the original FireFlies design, the possible colours, for both teacher and pupil, are red, yellow, green, blue and black (lights off). The choice was to keep this amount of colours, to maintain a low resolution of information. A high resolution or density of information (e.g. 10 possible colours) prevents a user to retrieve information without focused attention, which is often why ambient displays have a low resolution in information [22]. We believe the limited information density, physical action for

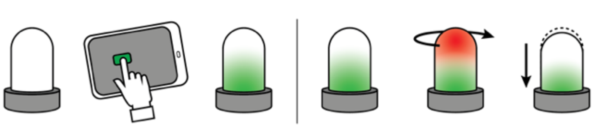

Figure 3. The teacher can change the *bottom* of the *light-object* via the app (left), the pupil can change the *top* by rotating the *light-object*, or turn it off by pushing it downwards (right).

Figure 4. The teacher application. Teachers can select a colour and apply it to one, by subsequently selecting a pupil, or all light-objects (bottom). The interface can be arranged by alphabet or table layout (right).

pupils to change colour and tangibility of the information is a good recipe for the system to blend into the environment and everyday routines.

To enable teachers to operate FireFlies2 in a manner that is meaningful to their personal teaching style, the meaning of each of these colours is not predefined but can be decided upon by the teacher using the system. In other words, similar to the original FireFlies, the design is open-ended. For example, depending on the agreements in the class, a light-object with a green bottom and a red top could indicate that the pupil is working very well (the green light may indicate a compliment from the teacher), but also has a question (indicated by the red top, as set by the pupil).

USER STUDY SETUP

FireFlies2 intends to display relevant information in the periphery of attention, either initiated by the pupil or the teacher. Making this information easily accessible, distributed over tangible objects in the classroom, could ensure that teachers no longer have to remember the information. Using FireFlies2 could therefore free up mental resources to allocate to other relevant tasks at hand, utilising distributed cognition. By deploying FireFlies2 in two classrooms for an extended period of time, our user study aimed to explore whether the design can be used in a meaningful way as part of the routine in the classroom and whether it indeed has the potential to lower the teacher's cognitive load. In addition, the study aimed to provide directions and ideas for future applications in educational technologies for supporting teachers in their everyday tasks.

The user study consisted of a deployment of two identical FireFlies2 sets in two different classrooms from one primary school for seven weeks. In total, four part-time teachers and 52 pupils participated, see Table 1 for an overview of their demographics. At the first day of deployment the teachers were introduced to the system and were able to try its functionality. The teachers then introduced and explained the system to their pupils. During the deployment, a researcher visited the participating teachers regularly (once per week), to check upon the system and engage in informal conversation. Quantitative data was gathered by logging all

Teacher	P1	P2	P3	P4
Age	45	35	49	47
Teaching Experience (years)	7	15	24	19
Teaching Time (days p.week)	3	2	3	2
Grade	4		3	
Pupils	25		27	
Pupil Age	7 - 8		6 - 7	

Table 1. Teachers (all female) and their pupils participating in the user study. P4 refrained participation after the 5th week.

interactions teachers had with the FireFlies2 app to control the colours of the light-objects. Specifically, we logged frequency and moments of interactions and colours that were used.

Qualitative data was gathered in interviews with teachers and in group sessions with pupils. During the seven weeks of deployment, four one-hour semi-structured interviews were held with each individual teacher; a *starting interview* at the beginning of the deployment, two *evaluation interviews* in weeks 5 and 7 of the deployment respectively, and an *exit interview* one week after the deployment had ended. The contents of these interviews and sessions are presented in the coming sections. Figure 5 shows a visual of the setup of the seven-week study, a period that was intermitted by a two-week school holiday. One teacher (P4) indicated that she had difficulties incorporating the user study into her busy schedule and therefore refrained from participation after the fifth week. Due to this, and one cancelled interview, a total of 13 semi-structured interviews were conducted.

Starting interview

The starting interview focused on gathering demographic information, understanding the teacher's approach to teaching, and establishing a view on the existing processes and routines within the classroom. This content was used to structure the evaluation interviews. Additionally, the functionality of the FireFlies2 system was demonstrated. The researcher explained that the teachers could choose how they would use the different colours of FireFlies2, and possible purposes of these colours were discussed.

Evaluation interviews

The interviews in the fifth and seventh week of use focused on the evaluation of FireFlies2 and its deployment. These interviews discussed how processes, routines and behaviours in the classroom changed with the deployment of FireFlies2. This enabled an in-depth discussion on the user experience of the system. Furthermore, the teachers were asked to give their opinion on the general functionality of the system, and on the workload during various teaching activities, with and without FireFlies2.

Exit interview

The final semi-structured interview focused on the teachers' experience one week after we had removed FireFlies2 from their classrooms. This could potentially uncover hidden routines or preferences around using FireFlies2, which would only be revealed after the system was no longer

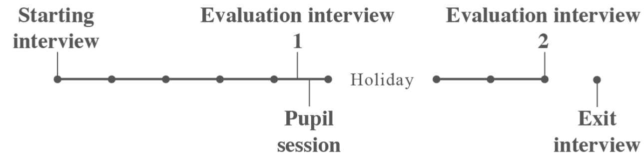

Figure 5. The user study setup including 7 weeks of use (with two weeks of holiday in between) by the two groups.

present. The teachers were hereby given the opportunity to give information concerning their experiences which they might not have said before.

Pupil session

To further understand the use and potential value of the FireFlies2 system, two group sessions were performed with the pupils in the two participating classes in the fifth week of the study. Given the young age of the participating children (6 to 8 years old), we decided to hold a session with the entire class involving various activities. This setting may be more comfortable for children compared to interviews (individually or in pairs) [23].

During the pupil session, the pupils were asked to draw onto three templates (showing a desk and an anonymous pupil) to create short scenarios (Figure 6). Specifically, pupils were asked to draw what they do when (1) asking a question to the teacher, (2) doing individual work and (3) seeing a neighbour's light-object change colour. For the first two scenarios, we asked the pupils to first draw how they did it before FireFlies2 was introduced, and second to draw how they do it with FireFlies2. In both participating classes, the teacher (P1 and P3) lead the assignment. While the pupils were drawing and writing, the researcher walked around and engaged in conversations with the pupils using their drawing to ask questions. Using this approach, the researcher aimed to identify the thoughts behind the pupils' drawings and texts. To conclude the assignment, the teacher discussed the assignment with all the pupils together. This enabled the pupils to share their final result and to express thoughts emerging during the discussion. The pupil sessions took about 90 minutes each.

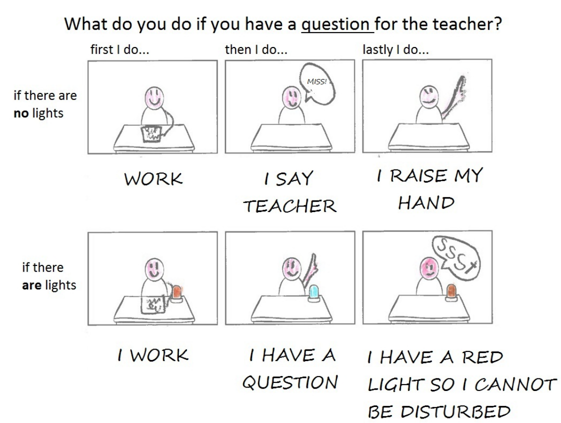

Figure 6. An example of a pupil's answer. The instruction text and text written by the pupil are translated for readability.

Qualitative data analysis

The interviews and the pupil sessions were audio recorded. The evaluation interviews were transcribed verbatim. The starting interviews were not transcribed as they were only used for the researchers to get accustomed with the context. The exit interviews were not transcribed, as the teachers did not share any additional information compared to the second evaluation interviews (which took place at the end of the deployment). From the pupil sessions, we noted observations and discussions that were related to the functionality of the FireFlies2 system. These notes were used as input for the evaluation interviews with the teachers.

In the analysis of these qualitative data, we were interested in how FireFlies2 was used as part of the teachers' routines, if and how it enabled distribution of cognition for the teachers and the possible effects of this distributed cognition in the classroom. Conform these research aims, we selected 51 quotes from the transcripts, which described or related to any cognitive processes (e.g. remembering, thinking, evaluating, interpreting), or which discussed differences (e.g. in cognitive workload) between the situation before and during the deployment of the FireFlies2. These quotes were analysed using open coding [30], an approach in which qualitative quotes are clustered without predetermined categories in mind, yet clusters emerge from the data presented. To minimise bias, the 51 quotes were divided amongst the first author and an independent researcher who was not involved in the study presented. Each researcher first clustered their set of quotes independently, after which the emerged clusters were discussed and a final set of clusters was agreed upon.

FINDINGS

Before we discuss our findings concerning integrating in everyday routines and distribution of cognition, we provide insights into the usage of the FireFlies2 system.

How FireFlies2 was used

To increase motivation of use, the purpose of the colours in FireFlies2 was not given beforehand, but chosen by the teachers in consultation with their class-colleague. Table 2 shows the chosen purposes for each participating class. As is shown, some colours were not used, as no relevant purpose could be thought of by the teachers (and pupils) involved.

		Class 1 (P1, P2)	Class 2 (P3, P4)
top	Red	Do not disturb me	Do not disturb me
	Green	I am available	I am available
	Yellow	I participate*	N/A
	Blue	I have a question	N/A
bottom	Red	Warning	Warning
	Green	Compliment	Compliment
	Yellow	N/A	N/A
	Blue	Attention	Come to Teacher

** introduced in week 3 by P1*

Table 2. Overview of the *light-objects'* colour purposes.

The FireFlies2 system was mostly used during independent work time, a teaching approach that was applied every day for 60 minutes in the participating classes. During these hours, pupils are required to work on exercises independently or in duos without nuisance. To illustrate, the pupils of P3 in class 2 placed their light-objects on their desks when entering the classroom. Teacher P3 then used the tablet to change the bottom of all light-objects to green (which meant all pupils work 'as is expected' from them, as no one misbehaved yet) and started her daily routine. Once the independent work hour started, she asked all pupils to set the top of their light-objects to red (indicating 'do not disturb me'), as they would start working in silence. P3 instructed the pupils that after five minutes they can rotate their light-object to indicate if they have questions (blue), are available to collaborate with other pupils (green), or are participating in the group activity (yellow), see Table 2.

During the day P3 used the tablet to give warnings and compliments to pupils, both during independent work hour and whole class instructions. At the end of the day the pupils left the classroom and P3 collected all light-objects to place them in the docking station, effectively turning off all light-objects.

The signals sent from the teacher app were logged to gain insights into the usage of the FireFlies2 by the teachers. Figure 7 depicts the number of signals sent, and differentiates individual signals (changing the colour of an individual student's light-object) from broadcast signals (changing all light-objects at once). Over the seven weeks of the study, 987 signals were sent by the teachers in class 1, and 619 by the teachers in class 2. Teachers from class 2 used the FireFlies2 system mostly to send signals to individual pupils (426 individual signals, 193 broadcast signals), whereas from class 1 mostly sent signals to the whole class (371 individual signals, 616 broadcast signals). This was confirmed in the interviews, as the teachers from class 2 indicated that they set pupils' light-object standard on green (a broadcast signal), on red when the pupil misbehaved (an individual signal) and back to green once the pupil recovered his/her behaviour (another individual signal). This is also visible in the use of colours in class 2, as show in Figure 7: green and red are used much more often than blue and yellow.

Qualitative Findings

The open coding [30] analysis revealed the following five clusters: *self-consciousness of behaviour, cognitive off-loading, class management, awareness of rules* and *visual*

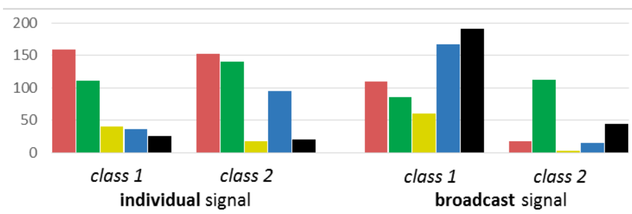

Figure 7. The distribution of signals from the teacher. The bar colour depicts the colour the teacher chose to communicate.

cues. Below we present the clusters and their content. Due to the user study being conducted with Dutch teachers and pupils, all quotes presented in this paper are translated to English from Dutch by the first author.

Self-consciousness of behaviour

The first cluster, containing 11 quotes, revolved around the pupils' behaviour. In particular, we found that the light-objects and their active colour(s) were used to promote and gain awareness of the pupils' behaviour.

For example, P3 indicated that one day she noticed that all pupils worked very well, given that almost no lights had been set to red, and she used this to compliment the pupils ("it [the light-object] didn't stay on red, with no one. […]" This is also what I discussed with them [the pupils]"). Additionally, P3 indicated that some pupils brought their lights with them to one-on-one conversations with the teacher: "then I asked 'why did you bring your light with you?', [pupil:] 'I also want it to be green'". This behaviour shows the pupils being motivated to keep their light-object green, and that the pupils relate their performance to their light-object.

Cognitive off-loading

The second cluster (4 quotes), provided clear examples of cognitive off-loading: a form distributed cognition, specifically the ability to store and retrieve knowledge at any time given [29] and thereby relieving memory resources. Teacher P1 used the yellow light for pupils to indicate if they were participating in the whole class instruction. She stated that these yellow lights enabled her to make no mistakes in remembering which pupils were participating; she could trust the system to reveal this information and she therefore did not have to remember or guess it. Normally, P1 would sometimes accidentally involve pupils who chose to work individually. With FireFlies2, she notices that "… they are not being disturbed if they are busy and I think they were participating but they are actually not". Concerning the use of the blue light to indicate that pupils had questions, P1 indicated that some pupils were able to put their question 'on hold' and continue working. The question would then be asked and answered after the teacher saw their blue light: (P1) "some kids said 'yes, I put it [the light] on it [blue] and I continue with the next assignment'". Some pupils however seemed not able to cope with this delay in getting an answer (P1): "some cannot wait and they do nothing until you come by". Setting cognition (in this case a question) aside to be retrieved later is a crisp example of distributed cognition.

Class management

During the interviews, the subject of class management occurred several times. 9 quotes related to cognitive processes and the FireFlies2 system revolved around practicalities, efficiency or communication as part of the teachers' class management. For example, P2 mentioned that with the use of FireFlies2 "… I walk around a lot less. That is why I cause less unrest. Alternatively, P1 experienced that by using the light-object she could steer the pupils to help each other: "Sometimes I ask a pupil: 'can you turn it to green? So other pupils, when I am working with a group here, can ask you something?' I then see other pupils walking with their notebook [to that pupil] and they do that very silently, which is great".

This cluster also contained experiences about differences in class management before and during deployment of the FireFlies2. P1, P3 and P4 indicated that FireFlies2 both introduced new tasks (more effort) and that it enabled existing tasks to become more efficient (less effort). P3, for example, stated that with FireFlies2, "I only have to press on red and they automatically look at you and know 'oh right'", which took less time and energy compared to correcting pupils, as was often done before the deployment of FireFlies2. However, P2 mentioned that when she had given a pupil a warning using a red light, it took effort to remember turning it back to green when the pupil corrected his/her behaviour. (P2) "…that is something you need to keep track of", as she did not want to keep the pupil believing that he/she was not working well. In this example, FireFlies2 required the teacher to actively 'undo' a warning, thereby introducing a new task that did not exist without FireFlies2.

Awareness of rules

This cluster contained 10 quotes related to the pupils' awareness of rules within the classroom. The teachers indicated that the colours of the light-objects controlled by the pupils themselves were used to discuss and increase awareness of the current rules in the classroom. For example, P3 uses a virtual traffic light on the interactive whiteboard to indicate rules. When this traffic light was set to red, all pupils needed to work in silence. When using this red traffic light, she asked the pupils to set their light-object to red as well: (P3) "'So where do you put your light on? Also on red. Because you cannot ask someone else, so the other colours are of no use.' This made them more aware of the traffic light". The teachers felt that due to pupils' setting the 'rule' themselves, the rules were emphasized and better upheld.

Visual cues

This cluster contains 8 quotes concerning the cues or information the light-objects provided. P1 and P2 indicated they gained an overview and new information with the use of FireFlies2. For example, they had a better overview of which pupils had questions: (P1) "... I look and I see, oops, there are already 3 questions [3 lights on blue]". And they also gained this overview more quickly than before: (P2) "I can see in one glance whether someone needs help or someone doesn't want to be disturbed". All teachers explained that the light-objects were easy to see. P2 also indicated that she trusted the lights to notify her if a pupil had a question: "…because I actually trusted those lights. I will naturally see whether someone is on blue and then I will go there for a moment".

From the 52 quotes 9 were not included in the named clusters, as they revolved around practicalities, e.g. P3: "those children need a lot of repetition", or P1: "Yes, that [the integration of the tablet in the routine] became a lot easier [over time]". In the next section we combine the logged data and qualitative findings to discuss the ability of FireFlies2 to provide distribution of cognition, the effects on the learning environment due to the distributed cognition that FireFlies2 potentially provides and the use of this research for future work.

DISCUSSION

This paper presented the 7-week deployment of FireFlies2 in two primary school classrooms with the aim to evaluate distribution of cognition as replacement for existing ways of working, and potentially free up mental resources of the teacher. In this section we further discuss the findings, focusing particularly on FireFlies2's *limitations*, its ability to *extend cognition in the classroom* and generalised findings related to *tangible distributed pixels.*

Limitations

The presented paper aimed at providing distribution of cognition in everyday activities within the classroom. The principle of peripheral interaction [7, 16], calm technology [34] and ambient displays [22] is to enable interactions that can shift between the centre and periphery of attention. If this shift is part of a user's routine, then the interaction is more likely to free up mental resources once the interaction is of less relevance. During the field deployment, several technical aspects prevented the designed interaction to become part of the teachers' and pupils' routines. The FireFlies2 design made it difficult to take the light-objects out of the charging station (or put them back in). Additionally, the teacher app occasionally froze, and required restarting. These problems prevented a fluent integration into the teachers' everyday routine. P3 indicated that her tempo was hampered during individual instruction, as she tried to call pupils forward by setting pupils' light-objects on blue, though the app froze occasionally. In addition, she did not wanted the pupils to put the light-objects in the charger by themselves, introducing a time-consuming task to her. These aspects resulted in P3 to abstain from participation in this user study in the 5th week.

Furthermore, the user study was conducted with two classes from different levels (class 1 with 7-8 years old pupils, class 2 with 6-7 years old pupils). The pupils from class 2 were in kindergarten before they joined their current class. The teachers from class 2 indicated that these pupils are still learning to obey classroom rules, to communicate and to listen. As the presented design relies on the users' ability to adhere to all these three, we, in hindsight, conclude that our findings could have benefited from a slightly older (e.g. as class 1) target group. Additionally, performing the study with classes from the same age could provide more consistent results.

Extending cognition in the classroom

The qualitative findings of our user study indicate that the use of coloured light-objects as replacement of current ways of working aided a number of cognitive processes. For pupils it helped to consider their performance and for teachers it helped to offload cognition by not having to remember things such as which pupils were participating or had questions. The FireFlies2 system thereby added value to the learning environment by presenting information, that otherwise would need to be remembered (e.g. red represented a 'previously' unwanted attitude). The pupils could see compliments, warnings and classroom rules presented in their light-object, whether they addressed individuals or the whole class, and could retrieve this information at any time given. Additionally, the represented information was visible for a longer period of time, making it possible for the users to retrieve the stored knowledge at another time given and whenever it is of relevance.

From the clusters self-consciousness of behaviour, cognitive off-loading and awareness of rules, most of the quotes revolved around pupils and their individual cognitive processes. 19 out of the 25 quotes in these clusters came from class 2. Class 2 mostly used the FireFlies2 system to communicate on an individual basis, as shown in Figure 7. The information presented by FireFlies2 about individual pupils enabled the teachers to gain an overview of the class, such as struggles in the overall progress when the majority of the pupils have red light-objects (meaning 'do not disturb'). It also enabled the teachers to get more detailed individual information when relevant; for example, if a teacher wanted to give a specific pupil a warning and saw that his/her light-object was already on red, the teacher sees a warning was already given. This can then be taken into account (e.g. taking additional measures if needed). This distribution of the light-objects also resulted in the location providing additional information, as the teacher could see specific locations in the classroom having patterns in their light-object. For example, one group of pupils with red light-objects can indicate that the pupils influence each other's behaviour and action needs to be undertaken. For pupils, the presence of a light-object on their own table stimulated that the message (e.g. warning or compliment) was received more personally. This was indicated by the pupils' consistent behaviour and response to colour changes in their light-object. For example, the teachers could set many light-objects collectively to red, which caused the pupils to respond accordingly, compared to a general verbal remark to the class, which some pupils ignored. Based on these findings, it seems that information at the level of individual pupils could offer more potential for distributed cognition compared to information at a class level.

According to the teachers, the colours on the pupils' desk aided the pupils to be self-conscious of their behaviour and performance. This became apparent when the teachers discussed with the pupils their performance at the end of the day. In addition, the pupils' ability to set their light-object's colour to indicate 'I am available' or 'do not disturb' seemed to stimulate pupils to more consciously consider their wishes. When the teachers asked the pupils to set their light-object to 'do not disturb' themselves at the beginning of the independent work hour, it seemed that this physical action emphasised the rules that were agreed upon, especially due to the physicality of the action according to the teachers. Once, after a few minutes, the pupils selected a colour of their preference, the teachers were able to address the pupils on their selection. For example, P1 asked a pupil that was working ahead if he is willing to switch from red to green, so other pupils could ask him questions if they wanted to. Before the FireFlies2 these preferences were not visible nor remembered, which indicates that the FireFlies2 system supports the cognitive processes of both pupils (considering their wishes) and teachers (not having to remember those wishes).

Tangible distributed pixels

The collective lights-objects formed a distributed display in the classroom. Two aspects of these 'tangible pixels' used in this research seem to have aided distributed cognition. In this section, we discuss these insights further and place them in the context of related work.

Similar to the Lanterns presented by Alavi et. al. [2] and the Subtle Stone by Balaam et. al. [8], the FireFlies2 lights were wireless and tangible and thereby gained additional meaning by their location. Not only did pupils grab their light-object and show them to the teacher, or bring them to a collaborative assignment, the teacher could also trust that the light-object on the table of the pupil, or near the pupil, corresponded with that pupil. Different from other related ambient displays in the classroom (e.g. Lernanto [3]), no mapping of information to location was needed. This enabled the teacher to immediately understand (for example) which pupils were participating in her instruction by simply glancing at the classroom. Different from prior work on FireFlies [5], the FireFlies2 light-objects could not only be manipulated remotely by the teachers, but also locally by the students themselves. The user study indicated that this visualized more (previously) hidden information, such as preferences of the pupils. Furthermore, this information affected the direct surroundings of the pupil, subtly communicating more than normally verbally spoken.

Similar to many ambient displays [22], the information resolution of FireFlies2 was low, which made the information easy to learn, understand and implement in the routine. The user study indicated that 4 colours were more than sufficient to start distributing information, as both classes used an average of three colours for both pupil or teacher operated colours. An interesting follow-up would be to include implicit data from pupils' digital learning environment. This could would result in information similar to what the Lanterns [2] represent (e.g. pupils' progress on their homework), though without requiring explicit interaction.

As elaborated on, the introduction of FireFlies2 also introduced new action possibilities and new tasks for the teacher. To minimize these, and thereby better adhere to the goal of this work, few improvements could be made. For example, an alternative on the tablet based app could improve the transition from intention to result. For example, when a teacher observes a pupil who (s)he thinks deserves a compliment (intention to give a compliment), the teacher grabs the tablet and makes a few taps to establish a green light (result). The prior design (FireFlies [5]) aimed to improve the time and effort to do so through peripheral interaction [7, 16] using a tangible body-worn input device. We believe such an approach would minimize the introduced tasks and thereby increase the cognitive benefit from the system as a whole. Another example could be to define a timer on certain colours, to prevent correction (e.g. a 'red' warning light turns off after 30 seconds).

Despite limitation of the study and the possible future improvements it revealed, we believe that deploying FireFlies2 in the real context of the classroom has shown potential for distributed peripheral displays to relieve teacher's cognitive load. As future work, we intend to explore other types of data (e.g. from the electronic learning environment) presented on the FireFlies2 system to further support teachers in their everyday practice.

CONCLUSIONS

The paper presented elaborates on a seven-week field deployment of FireFlies2, a distributed tangible information system for primary education. The user study aimed at enabling distributed cognition as aid in the learning environment. Analysis of usage data and semi-structured interviews revealed a number of examples in which FireFlies2 supports cognitive processes of teachers and pupils. In particular, FireFlies2 showed potential to support pupils in reflection on performance and behaviour, and to support teachers in offloading relevant information (which would otherwise need to be remembered) onto the system. This paper provides a demonstration of how HCI might lower the cognitive workload of users. This paper also contributes to the development and design of classroom technologies, especially to aid current activities in learning environments.

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