Playful Toothbrush: UbiComp Technology for Teaching Tooth Brushing to Kindergarten Children

Yu-Chen Chang[1], Jin-Ling Lo[3], Chao-Ju Huang[1], Nan-Yi Hsu[3], Hao-Hua Chu[1,2], Hsin-Yen Wang[3], Pei-Yu Chi[2], Ya-Lin Hsieh[3]

[1]Department of Computer Science and Information Engineering, [2]Graduate Institute of Networking and Multimedia, [3]School of Occupational Therapy, National Taiwan University

{b92902021, julialo, b92902091, b91409039, haochu, b91409037, r95944005, b92208024}@ntu.edu.tw

ABSTRACT

This case study in UbiComp technology and design presents a "Playful Toothbrush" system for assisting parents and teachers to motivate kindergarten children to learn proper and thorough brushing skills. The system includes a vision-based motion tracker that recognizes different tooth brushing strokes and a tooth brushing game in which the child cleans a virtual, mirror picture of his/her dirty teeth by physically brushing his/her own teeth. The user study results suggest that Playful Toothbrush enhances the effectiveness of kindergarten children in brushing their teeth, as measured by number of brushing strokes, duration of brushing and thoroughness of teeth cleaning.

Author Keywords

Ubiquitous computing, occupational therapy, persuasive technology, children, tooth brushing.

ACM Classification Keywords

H5.2. Information interfaces and presentation (*e.g.*, HCI): User Interfaces.

INTRODUCTION

Encouraging new behaviors or modifying existing ones in young children are vital and challenging tasks for parents and teachers. Most occupational therapists confer that parental verbal persuasion alone is inadequate for motivating behavioral change in children. As a result, play-based occupational therapy has been developed to induce behavioral change [28] by leveraging the desire of children to play. Although play-based treatment programs have demonstrated effectiveness in children, they have two general limitations. First, children are often treated in clinics during regular appointment hours, at which time behaviors such as poor eating and sleeping habits are not observable. Second, since such functional behaviors are not observable, direct intervention by therapists is not possible.

Opportunities for UbiComp Technology

To address these two limitations, pediatric occupational therapists often use indirect approaches to training children in performance components via play activities [16]. When a child acquires the general skills needed to perform an activity, he/she is assumed to be able to successfully perform the activity. However, this is not always true, particularly in habit training, because activity performance is the result of interaction of person, activity and environment [10]. A more direct approach is to make the target functional activities playful to engage children into active participation, so that children's functional performance of the target activities can be enhanced directly. UbiComp technology provides new opportunities to extend the reach of occupational therapists from their treatment clinics into the everyday environment of a client by (1) implementing more direct and more effective behavior intervention programs and (2) targeting the specific functional behavior of a client at the naturalistic environment at which the behavior occurs.

Targeting tooth brushing behavior in kindergarten children

This work targets tooth brushing behavior in kindergarten children. Proper and thorough brushing is essential for effectively cleaning teeth and gums and for preventing dental caries [5]. This study specifically targeted oral hygiene in kindergarten children because, by the time these children reach school age, they are expected to assume responsibility for maintaining their oral hygiene. The average 5-year-old child brushes only 25% of sixteen areas of teeth [29]. Since young children are often deficient in brushing their teeth thoroughly and uniformly, supervision of parents and/or teachers is needed to teach them proper brushing techniques [9]. However, due to the limited manual dexterity and cognitive ability of young children, parents and teachers often have difficulty instilling proper and thorough tooth brushing habits in young children. Therefore, the goal of Playful Toothbrush is to extend effectiveness of adult supervision in teaching proper brushing technique to young children, not to replace adult supervision.

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Several commercial products have been developed to entice children to brush, such as sugary toothpaste from Colgate [6], the ToothTune toothbrush with musical feedback from Hasbro [13], *etc.* Although these products may attract the interest of children, in brushing, they still fall short in teaching children to brush properly and thoroughly.

This study designed and evaluated a prototype Playful Toothbrush system as an assistive tool for helping parents and teachers instruct young children in proper tooth brushing. The user study results described in detail below suggest that using the proposed Playful Toothbrush system can improve tooth brushing technique in kindergarten children, resulting in more effective teeth cleaning, increased number of brushing strokes, longer brushing time and more thorough cleaning. The design of the proposed system is based on the principles of play-based occupational therapy. This system leads children to view tooth brushing as an enjoyable, interactive game. Therefore, tooth brushing becomes a game, and young children learn proper tooth-brushing habits by actively participating in the game.

The design of the system reflects the two purposes of the Playful Toothbrush system. First, for children who dislike brushing their teeth, the goal of Playful Toothbrush is to make the task more attractive, similar to the Hasbro ToothTune [13] product. For children who already brush their teeth habitually but not properly and thoroughly, the goal of Playful Toothbrush is to teach proper brushing technique. These two purposes require different strategies in game design. For the former purpose, the game should be simple and playful to attract children to perform the task of brushing teeth. For the latter purpose, the game must engage children in learning proper tooth brushing. An effectively designed game would not only require children to perform the activity but must also consider the required physical and cognitive functions needed by children to learn proper brushing technique by playing the game. To achieve the learning objective, teaching-learning theory is applied in the game design.

UBICOMP TECHNOLOGY IN PLAY-BASED TOOTH BRUSHING BEHAVIOR INTERVENTION

Teaching proper brushing habits in young children requires identifying (1) the proper brushing technique for young children and (2) an effective teaching method. Regarding the first concern, the horizontal scrubbing method is preferred because it is the most natural technique and is adopted automatically [21] by children. For plaque removal, horizontal scrubbing is comparable if not superior to other techniques such as the roll, Charters and modified Stillman techniques [2]. Additionally, to teach young children to clean all teeth efficiently and thoroughly, a systematic brushing sequence can help young children remember to brush all areas [32]. A brushing sequence suggested by the Bureau of Health Promotion in Taiwan is currently taught to all kindergarten students. The recommended sequence starts with brushing from the buccal aspect of the teeth in the maxillary right quadrant all the way to the left followed by brushing the occlusal surface of the teeth in the maxillary left quadrant and the lingual aspect of the teeth from the left back to the right. The final area brushed is the occlusal surface of the teeth in the maxillary right quadrant. After brushing the teeth in the maxilla, the teeth in the mandible are brushed in a similar sequence (Figure 1).

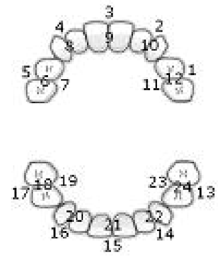

Figure 1. Twenty teeth divided into twenty-four brushing areas; each area has a specified order in the brushing sequence.

Given the complexity of correct tooth brushing, young children may have difficulty learning proper and thorough tooth brushing skills by themselves. Tooth brushing ability has been associated with maturity of visual-motor integration [27] and language comprehension [31]. However, because tooth brushing requires both physical and psychological functions, only developmental age has proven significantly predictive of how effectively children remove plaque during brushing [9]. To elucidate tooth brushing skill in young children, Ogasawara *et al.* [23] divided the oral cavity into sixteen regions. With a 3-step instruction method (verbal instruction → modeling → physical guidance), children older than age five could be taught to thoroughly brush all regions within the oral cavity [23]. Leal *et al.* [19] investigated the effectiveness of three different methods for teaching tooth brushing to kindergarten children. Leal found that children aged 3 to 6 learned best by direct individual instruction followed by audiovisual modeling; "modeling only" was least effective.

Based on the findings above, correct tooth brushing can be taught to children 5 years or older by combining audiovisual modeling with direct observation and personal guidance. However, this method is both laborious and time consuming. For example, one training session may take 10-15 minutes to teach one child [34]. Because 6-year-olds have not developed a good body scheme in oral cavity, to teach them brushing all teeth areas is not only difficult but also frustrating for parents (or therapists) and children. Further, to motivate children to play an active role in tooth brushing, immediate reward following a good performance is necessary [14].

The past experience [20] of the authors indicate that a proper combination of UbiComp technology and play-based occupational therapy can not only help therapists and parents implement a more effective behavior intervention program but also provides children with a stronger incentive to perform the target activity than play-based occupational therapy alone. Restated, UbiComp technology is intended

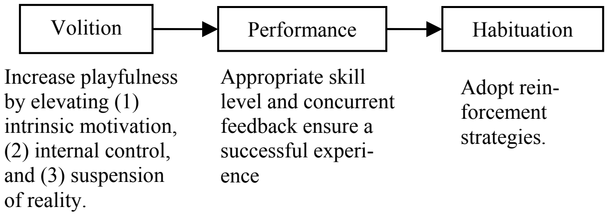

Figure 2. The proposed play-based occupational therapy model

to enhance, not replace, the effectiveness and efficiency of instructional guidance from parents and dental therapists.

Play-based brushing intervention program

The proposed play-based brushing intervention program was based on the model of human occupation (MOHO) [15]. According to MOHO, occupational behavior such as tooth brushing requires the organization of three personal subsystems: volition, performance capacity and habituation. To develop proper brushing habits, children must have sufficient motivation as well as the physical and mental functions needed to perform tooth brushing. As Figure 2 shows, a play-based occupational therapy model based on MOHO was used in designing the Playful Toothbrush system. In this model, the three subsystems are facilitated by applying theories of playfulness and reinforcement in the design. According to theories of play and playfulness, play comprises three primary elements: intrinsic motivation, internal control and suspension of reality [3]. Intrinsic motivation refers to the tendency of learners to pay more attention to the process than to the product or outcome. Restated, the activity itself rather than its consequences attracts learners to actively participate. Moreover, internal control is defined as the extent to which individuals are responsible for their actions and at least some aspects of the activity outcome. Suspension of reality refers to the role of imagination during play. The three elements of play comprise the foundation of activity design. Performance capacity refers to individual physical and cognitive capability to perform a target activity. The challenge of the proposed toothbrushing game must match the capability of the target subjects, kindergarten children, and provide them with a positive experience while learning tooth brushing skills. Positive reinforcement following proper brushing behavior can further strengthen this behavior until it becomes sufficiently ingrained.

Figure 3 shows how these principles were applied in designing Playful Toothbrush videogame. The child is presented with a virtual image of his or her own uncleaned teeth on an LCD display. The system provides guidance in systematic brushing and immediately rewards the user after each good performance to ensure an effective learning experience. The goal of the system is to teach a young child to thoroughly clean the virtual uncleaned teeth using his/her own physical tooth brushing motions as input. For example, the action of a user brushing his/her outer left teeth is mapped to a graphic display of the virtual outer left group of teeth being cleaned on the LCD mirror image with areas

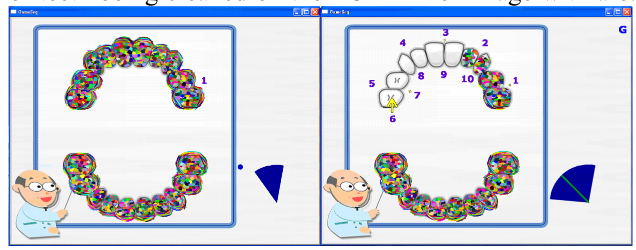

Figure 3. Brushing game screenshots. (a) At the start of the game, all virtual teeth are colored to represent plaque buildup. The suggested brushing order is indicated by a sequence of numbers in each teeth area. (b) Areas 1-9 have been cleaned, and the user is beginning to brush area #10.

of plaque appearing to fall away when the corresponding teeth are properly brushed. To guide the child in brushing systematically, the starting area is indicated by a “1” on the mirror image of the maxilla on the right side of the screen. After brushing this area, a “2” appears to indicate the next area to be brushed. In each of the twenty-four areas of teeth (Figure 1) is a graphic representation of seven layers of plaque which must be removed. Each proper brush stroke produces a graphic representation of a layer of plaque being removed, accompanied by audio feedback comprised of notes on the diatonic scale, starting with “Do.” Incorrect brushing technique elicits no response. After all seven notes (Do, Re, Mi, Fa, So, La and Ti) on the diatonic scale are heard, all teeth appear sparkling white. This design can teach children the duration of brushing needed to thoroughly clean each area of teeth. Further, the progression of notes on the diatonic scale provides the child with audio feedback of progress while the virtual image of teeth being cleaned simultaneously provides visual feedback. The changing tones and visual images motivate the child to participate in the game and complete the brushing of all the teeth, and also provide the child with a sense of control in the activity. With active participation and the well-defined criteria of acceptable brushing behavior, the child is given an appropriate level of challenge and gains a sense of personal competence and achievement. The activity is thus self-reinforcing, and the child is induced to complete the activity. In summary, the proposed toothbrush game design applies the three elements of play with principles of teaching-learning theory to motivate children to actively participate in learning to brush their teeth properly and thoroughly.

DESIGN CONSIDERATIONS

Based on the above play-based occupational therapy model, the following three main features were considered in designing the Playful Toothbrush system: (1) enjoyment of game playing to achieve volitional change (motivation) in child behavior, (2) engagement to minimize the performance needed for a satisfying game playing experience and (3) automation to help children learn tooth brushing skills and internalize them as a habit.

Figure 4. The brushing tracker uses a web camera anchored on a mirror to track an LED-coded toothbrush extension. The brushing game appears on an LCD display

UbiComp technology provides the enjoyment of game play, which can produce volitional change. As mentioned earlier, for children, "play is a way of learning [1]." The proposed system uses play to make the target activity itself enjoyable. On one hand, children are continuously motivated by immediate feedback that is clearly understandable and prominently featured during the game. On the other hand, the game offers sufficient challenge instill a sense of achievement in children.

The second design consideration is engagement. Since tooth brushing is the target activity, the natural tooth brushing action of children was used as game input. Once children are attracted by the game, they must actively brush their teeth to continue playing. This engagement design thus causes children to associate tooth brushing with game play and having fun.

The third design consideration is automatization. After children learn to brush their teeth effectively using this device, the learning of tooth brushing should be internalized, *i.e.*, children must perform the activity habitually. The proposed design should avoid unnecessary involvement of instructors or other adults which could interdict the motor planning of users and cause them to become passive. Instead, the game is designed to respond positively and immediately to correct brushing action so that children feel motivated to continue. Through constant repetition, children can acquire proper brushing skills and use them habitually. At that stage, the system is no longer needed and can be withdrawn.

PROTOTYPE DESIGN

Figure 4 shows the Playful Toothbrush system. The two main components are (1) a vision-based brushing tracker comprised of a web camera with a brush extension coded with LED marker patterns; (2) a brushing game presented on the LCD display which uses tooth brushing motions as game input.

As mentioned in the previous section, the horizontal scrubbing (HS) method is currently the most widely accepted brushing method and is the most commonly taught to kindergarten children. Therefore, the HS method was adopted as the activity model for the brushing tracker system. The system also incorporated brushing guidelines from the Taiwan Bureau of Health Promotion. As Figure 1 shows, the proposed modified HS method classifies twenty teeth and forty-eight tooth surfaces (occlusal, inner and outer surfaces) into twenty-four areas. Each area of teeth has two tooth surfaces, and each surface has one correct brushing motion. These twenty-four brushing motions define the set of activities which the brushing tracker system is programmed to recognize.

For an optimal learning environment, the brushing tracker system must recognize brushing behaviors both accurately and in real time so that users can immediately receive correct and just-in-time game feedback corresponding with their behavior. We first tested using 3D accelerometers embedded into toothbrushes to recognize brushing behaviors. However, although the speed of the accelerometer-based system was adequate, but it could not accurately distinguish between the twenty-four teeth areas in the proposed system. Therefore, the vision-based approach described below was employed that can provide both accuracy and real time performance.

Vision-based brushing tracker system

An intuitive, direct vision-based system captures and tracks the areas where the brush bristles scrub the teeth. However, this direct approach is problematic because the brush-teeth contact area cannot be monitored by an external camera when the mouth is closed during brushing. Therefore, to infer the area being brushed, an indirect approach was adopted to analyze the angle and orientation of the brush handle, which are constantly visible externally.

The vision-based brushing tracker consists of two components. The first component is a box-shaped brush extension (Figure 5) with four rectangular faces (*A, B, C* and *D*, where face *A* corresponds with the tips of the toothbrush bristles). Each face is coded with LED markers showing unique patterns distinguishable for computer vision. A stem on the brush extension can be affixed with VELCRO to the end of a standard toothbrush. The second component is a web camera positioned above the user to capture an overhead view of the toothbrush extension movement.

Modeling horizontal brushing strokes

The vision-based brushing tracker system recognizes twenty-four brushing strokes for each of the twenty-four teeth areas in Figure 1. To accurately differentiate the twenty-four brushing strokes, the three main elements of a physical brushing stroke were modeled. Flight dynamics

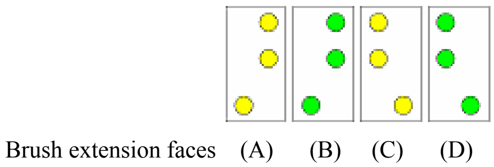

Figure 5. Unique LED marker patterns (from left to right: yellow clockwise, green clockwise, yellow counter clockwise, and green counter clockwise) encoded on the four faces (A, B, C and D) of the brush extension.

terminology was used to describe the physical orientation of the strokes. A tilt over the *x* axis is a "roll with a rolling angle (θ_{roll})," and a tilt over the *z* axis is a "yaw with a yaw angle (θ_{yaw})." These three elements can then be described as (1) bristle roll angle (θ_{roll}) on the *x* axis, (2) brush yaw angle (θ_{yaw}) on the *z* axis and (3) brush movement and motion vector.

Since the teeth-bristle contact area is not externally visible during brushing, the bristle rotation and brush orientation angles are combined to infer the motion required to brush a specific teeth-bristle contact area using a horizontal scrubbing motion. For example, brushing the biting surface of the maxillary molars (teeth area #6 in Figure 1) requires (1) holding the bristle upward at a rolling angle of $\theta_{roll} = 90$ degrees and (2) turning the brush on the flat plane at a yawing angle of $80 < \theta_{yaw} < 150$ degrees. In addition to the bristle rolling and brush yawing angles, the user must (3) move the brush back and forth with a brush motion vector displacement exceeding 1.5 centimeters and a direction of brush motion vector (θ_{yaw}) in the range of 80~150 degrees.

Brushing Tracker Algorithm

Figure 6 displays the vision-based brushing tracker algorithm. Step (1) is to filter out excessively dim/bright pixels from the camera image which are unlikely to be produced by the LED light sources on the brush extension. Step (2) is to cluster the remaining nearby pixels into groups, each of which corresponds to one LED light source. These clusters indicate the locations of at least three LED lights (from one brush extension face) on a camera image.

Step (3) is reconstructing the brush/bristle rolling & yawing angles. First, the brush extension face, which is pattern-coded in accordance with Figure 5, is identified in the camera image by color (yellow or green) and the relative positions of the LED lights from the previous step. Since a camera image may simultaneously capture two brush extension faces (*e.g.*, the brush extension is tilted at a 45 degrees angle to the camera viewing plane), the tracking algorithm can simultaneously detect both faces After the brush extension face is determined, the brush yawing (θ_{yaw}) angle as well as the brush/bristle rolling angle (θ_{roll}) can be calculated. For example, when the camera captures the brush extension showing face *A* oriented upward toward the camera viewing plane, it maps to a bristle rolling angle (θ_{roll}) approximately 90 degrees (*i.e.*, 90 degrees in the camera coordinate system, or 65 degrees in the global coordinate system).

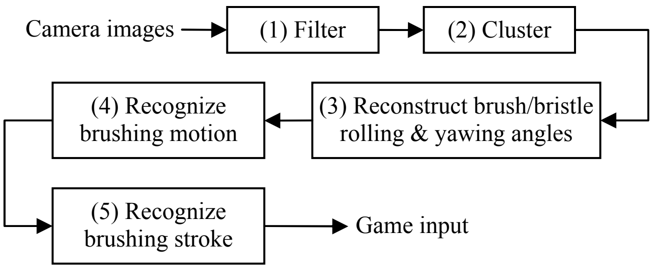

Figure 6. Brushing tracker algorithm

Step (4) is recognizing the brushing motion vector. The brush motion vector (*v*) is computed by tracking the movement of the brush extension face across consecutive image frames. This brush movement is calculated by tracking the displacement of the LED lights on the brush extension. Experimental observations of children brushing indicate a brushing movement usually produces about 1*cm* ~ 2*cm* of motion displacement (*i.e.*, matching the 2-tooth length in each teeth group) between consecutive frames from the camera viewing plane. The following rule was effective for recognizing brushing strokes: at least eight of twelve consecutive image frames with brushing motion vectors satisfying the following two conditions: (1) vector length within 1*cm* ~ 2*cm* and (2) vector direction within ±10 degrees of the correct direction of motion for brushing the target teeth area according to the modified HS method.

Step (5) is to recognize brushing stroke. First, the brush yawing angle (θ_{yaw}), the bristle rolling angle (θ_{roll}) and the brushing motion vector (*v*) calculated from previous steps must be transformed from the camera side-view coordinate system to the global coordinate system. Second, a mapping table is calibrated a-priori to match a set of $(\theta_{roll}, \theta_{yaw}, \{v\})$ values to a brushing stroke in a specific teeth area. Note that random non-brushing motions are likely to have no match in this mapping table. By applying this mapping table, the brushing tracker system can recognize valid (or invalid) brushing strokes in a specific teeth area. The recognized brushing stroke is then used as input to the brushing game described below.

Additional implementation details

To effectively implement the system, three important considerations were constructing the toothbrush extension and camera placement. The toothbrush extension was required to be extremely lightweight for easy use by children as well as water-proof to prevent water from entering the brush extension and short-circuiting the LEDs. The current prototype toothbrush extension consists of a 2*mm* acrylic board weighing 10 grams with dimensions of 3.2*cm* * 1.7*cm* * 1.7*cm*. To prevent a child from holding the brush extension area (thus blocking the LED patterns from the camera), a wider circular plate is added atop the toothbrush extension as a separator from the brush handle. Since the LEDs extend from the end of a brush handle, it does not physically block of brush handle. Therefore, a child held the brush handle naturally. The second consideration is camera placement enabling a clear view of the brush extension during brushing. If the camera position is too low, the brush extension would easily extend beyond the camera field of view. If the camera position is too high, the brush extension would be small and unclear in the camera view. Additionally, the camera viewing angle is also important for providing appropriate viewing coverage. Experimentation with various position revealed the ideal position for the web camera (the LiveCam from Creative Technology) was at a 65 degrees angle to the flat plane and approximately 40*cm*/60*cm* forward/above the mouth of the user. The third consideration is that as some child subjects were left-handed, our system recognized brushing strokes from both right-handed and left-handed children.

Accuracy of the brushing tracker system

Two experiments were performed to measure the accuracy of the vision-based brushing tracker. In the first experiment, a trained adult performed a standard horizontal tooth brushing motion using the Playful Toothbrush. The brushing session was recorded by a video camcorder, and the video recording was analyzed by a human observer to determine the actual number of brushing strokes (ground truth) performed. The recognition accuracy calculated by the number of vision-recognized brushing strokes over the actual number of brushing strokes was 98.6%. This experiment demonstrated the accuracy of the brushing system under ideal conditions (*i.e.*, without random or erratic behavior by young children).

The second experiment analyzed data from the 5th training day of the user study (described in Section 4). The effectiveness of the system was analyzed in thirteen kindergarten children aged 72-81months. Since young children tend to exhibit many unpredictable brushing or non-brushing behaviors, recognition errors increased. The error rates were calculated as follows. First, 48 minutes of child brushing videos were analyzed by an occupational therapist to identify the actual brushing strokes performed. Recognition accuracy was then computed as the duration of all tracker-recognized brushing strokes divided by the duration of actual brushing strokes. The 93.2% recognition accuracy in these thirteen children was considered acceptable. The user study showed no indication that recognition errors confused or otherwise affected the subjects.

Brushing game

The brushing game was designed to guide the user to brush in accordance with the rules of the modified horizontal brushing method. The Taiwan Bureau of Health Promotion recommendation is ten strokes for each tooth group. Since the brushing tracker did not recognize all possible brushing strokes, the game design required the child to remove seven layers of plaque. This experience indicated that removing seven virtual layers of plaque requires approximately ten physical brushing strokes. The modified horizontal brushing techniques require a total brushing time of approximately 2 minutes (120 seconds). When the total brushing time is equally divided among the twenty-four teeth areas (Figure 1), each teeth area should receive approximately 5 seconds of brushing. The modified horizontal brushing technique also recommends approximately seven back-and-forth brushing strokes to clean each teeth area; thus, the duration of each stroke should approximate 0.71 seconds.

Figure 3 shows two screen shoots of the brushing game. The current physical brushing motions of the user are recognized by the vision brushing tracker as input to a game shown on the LCD display. Figure 3 (a) shows the virtual image of uncleaned teeth displayed at the beginning of the game. Each tooth is completely colored to represent plaque accumulation. The goal for the child is to thoroughly clean the virtual teeth using his/her own physical tooth brushing motions as game input. Each correct brushing stroke recognized by the brushing tracker causes one layer of plaque to be removed from the teeth. As described previously, the brushing game is configured with seven layers of plaque per teeth area. After cleaning all seven layers of plaque, an animation of sparkling white stars appears on the cleaned teeth. In addition to the above visual feedback, the brushing game also provides audio feedback: each successful brushing stroke is indicated by a musical note on the progressive 7-note diatonic tone (Do-Re-Mi-Fa-So-La-Ti).

The brushing game suggests a brushing sequence for the child to follow by indicating the current target area of teeth with a number (*i.e.*, the child should brush this area now). Brushing other areas of teeth produces no game response or reward. After detecting seven brushing strokes in the current brushing area, a number appears in the next area to be brushed. When the child follows the brushing order and finishes cleaning all teeth, the virtual teeth appear completely white and an applause sound is heard.

USER STUDY

This section describes the results of the user study, which was guided by the following inquiries.

- How effective is the Playful Toothbrush system in improving the brushing skills of users?
- What aspects of brushing behavior were affected by use of the Playful Toothbrush system?

Subjects. Thirteen kindergarten children with a mean age of 77 months (range, 72-81 months) participated in this toothbrush training program. The five girls and eight boys were from middle class families, and all were residents of Taiwan at the time of the study. The parents of all participating children gave informed consent to the study.

Procedure and measures. The user study was conducted in a kindergarten in which all children are required to brush their teeth daily after meals or snacks. Therefore, tooth brushing is a habitual activity for these children. The Playful Toothbrush system (including game display, camera, *etc*.) was installed at the sink in the restroom where these children normally brushed their teeth. As Figure 4 shows, the game display was positioned on the mirror above the sink enabling comfortable observation by the user during the game. A second video camera was used to record the brushing performance of each subject for behavioral analysis.

All thirteen children in the study brushed their teeth once a day during 11 kindergarten school days. The first day was a pre-trial practice run to explain the Playful Toothbrush system and the expected brushing activity as well as to introduce the therapists.

The actual user study trial was performed during the remaining 10 days. The four phases of the trial were (1) pre-test, (2) training, (3) posttest and (4) follow-up. During the two-day pretest phase (days 2-3 on Fri./Mon.), the child subjects were asked to brush their teeth using their own toothbrushes (*i.e.*, without the Playful Toothbrush) with brushing methods they were accustomed to using at home. The training phase consisted of 5 days (days 4-8 on Tue.-Fri. and the following Mon.) during which the child subjects used the Playful Toothbrush. In the 2-day posttest phase (days 9-10 on Tue./Wed.), subjects brushed using their own toothbrushes (i.e., *without* using the Playful Toothbrush). However, before brushing on these 2 days, the subjects were asked to mentally recall how they brushed previously using the Playful Toothbrush. The one-week follow-up phase was a single day (day 11 on the following Mon.) on which the subjects were again asked to brush using their own toothbrushes.

Since 6-year-olds could not learn how to play the brushing game automatically by only watching the virtual mirror image of their teeth, an occupational therapist was present to observe children while they brushed teeth. The therapist's role during training is like a parent motivating and guiding the children how to play the brushing game, but not to teach teeth brushing directly. The therapist was there to assist whenever children need help playing the game.

To measure how effectively the subjects brushed their teeth, the tooth brushing effectiveness was measured on the following 7 days: second day of pretest (day 3), every other training day (days 4, 6 and 8), both posttest days (days 9-10) and the day of one-week follow-up (day 11). The measurement method used a special plaque-disclosing dye/agent (*i.e.*, FDC red #28) that attaches to plaques on tooth surfaces. Children swished the dye in their mouths before each brushing session. Before and after each brushing session, each child was orally examined to evaluate the presence of plaque on their teeth. The measurement method was adapted from the Plaque Control Record [24], which calculates the *plaque index* as the number of teeth surfaces with visible plaque divided by the total number of tooth surfaces. This study slightly modified the Plaque Control Record [24] in that five surfaces (mesial, distal, buccal, lingual and occlusal) were measured for the molar teeth.

	Before brushing Mean(SD)	After brushing Mean(SD)	Cleaning effect Mean (SD)
Pre-test			
Day 3	0.69(0.25)	0.37(0.18)	0.32(0.21)
Training			
Day 4	0.76(0.14)	0.09(0.10)	0.67(0.15)
Day 6	0.68(0.28)	0.04(0.05)	0.64(0.26)
Day 8	0.79(0.18)	0.11(0.10)	0.68(0.17)
Average	0.74(0.19)	0.08(0.06)	0.66(0.17)
Post-test			
Day 9	0.83(0.11)	0.16(0.10)	0.67(0.13)
Day10	0.86(0.16)	0.15(0.08)	0.70(0.15)
Average	0.85(0.10)	0.16(0.07)	0.66(0.28)
Follow-up			
Day 11	0.88(0.14)	0.18(0.10)	0.70(0.14)

Table 1. Plaque index of children before and after each brushing session. The cleaning effect was computed by subtracting the before-plaque index from the after-plaque indices. (n=13)

In addition to using the plaque disclosing dye, the brushing videos were also analyzed and coded. The following data were counted for each child brushing session: total brushing time, number of brushing strokes in each of twenty-four teeth areas and total number of brushing strokes. All video analyses and coding were performed by an occupational therapist trained to identify the behaviors of interest. To ensure coding consistency, the following coding procedure was observed. Prior to actual coding, the therapist *twice* coded the thirteen child subjects using the pre-trial video recorded on day 1. The second coding was done two days thereafter. The intraclass correlation (ICC) [30] between these two coding procedures was 0.97, and the ICC for brushing each teeth area was 0.96. The ICCs indicated good coding reliability.

Results. Table 1 shows the 7-day results indicated by the plaque disclosing dye. The cleaning effect was measured by the difference in plaque indices measured before and after each brushing session. Three main findings were as follows. (1) Wilcoxon Signed Ranks Test revealed a significant difference ($p < 0.1$) in teeth cleaning effectiveness between pretest phase (without Playful Toothbrush) and training/ posttest phases (with Playful Toothbrush). The mean cleaning effectiveness doubled from 0.32 to 0.66. (2) No statistically significant difference was noted between training, posttest and one week follow-up, which suggested that teeth cleaning effectiveness was retained from training (with Playful Toothbrush) through posttest and one week follow-up (without Playful Toothbrush).

Column 2 of Table 2 shows the average number of brushing strokes performed by each of the thirteen subjects on each day during pretest, posttest and one week follow-up. The data were obtained by coding and analyzing the video recordings. The Wilcoxon Signed Ranks Test revealed a statistically significant increase in the number of brushing strokes ($z=-2.20$, $p<0.5$) from pre-test (190.46 strokes) to post-test (248 strokes). No significant difference was observed between post-test (248 strokes) and one-week follow up (239.62 strokes).

	Number of brushing strokes Mean(SD)	Number of unbrushed teeth areas Mean(SD)	Brushing time Mean(SD) (sec)
Pretest			
Day 2	212.31(137.77)	11.31(5.25)	84(53)
Day 3	168.62(157.03)	13.46(5.35)	67(46)
Average	190.46(138.38)	12.39(4.75)	76(45)
Training			
Day 4			292(86)
Day 5			265(42)
Day 6			252(57)
Day 7			242(46)
Day 8			239(54)
Average			251(39)
Posttest			
Day 9	281.69(120.66)	7.46(4.89)	137(41)
Day 10	214.31(71.91)	9.46(5.12)	99(31)
Average	248.00(87.12)	8.46(4.82)	118(30)
Follow-up			
Day 11	239.62(107.48)	8.31(5.07)	120(36)

Table 2. User study results in thirteen subjects on a given test day. The second column shows the average number of brushing strokes, the third column shows the average number of unbrushed teeth areas, and the fourth column shows the average brushing time.

Column 3 of Table 2 shows the average number of unbrushed teeth areas in the thirteen subjects on each day of pretest, posttest and one week follow-up. Wilcoxon Signed Ranks Test revealed a statistically significant decrease in the number of unbrushed teeth areas *(z=-3.19, p<0.1)* between pretest (12.39) and posttest (8.46). Similarly, the number of unbrushed teeth areas significantly decreased *(z=-2.90, p<0.1)* between pretest (12.39) and one-week follow up (8.31). No statistical difference was noted between posttest (8.46) and one-week follow up (8.31).

The average brushing time in the thirteen child subjects on each day of the 10-day trial is shown in the fourth column of Table 2. Wilcoxon Signed Ranks Test revealed a statistically significant increase in brushing time *(p<0.1)* from pretest (76 seconds) to training (251 seconds) *(z=-3.06, p<0.1)*. Mean brushing time from pretest (76 seconds) to posttest (118 seconds) also significantly increased *(Z=-2.69, p<0.1)*. However, brushing time at posttest (118 seconds) and at one-week follow up (120 seconds) did not significantly differ.

The children have been trained to brush their teeth by the kindergarten teachers with oral instruction and demonstration before the pretest phase, so that the children learned and developed proper after-meal brushing habits. However, their teeth cleaning effectiveness was poor. The user study indicated that, overall, the subjects failed to properly clean 37% of teeth surfaces (Table 1). However, after training with the Playful Toothbrush system for five consecutive school days (including a one-weekend interval), all subjects significant improved in teeth cleaning effectiveness (Table 2), number of brushing strokes (Table 2), length of brushing time (Table 1) and coverage of teeth areas (Table 2). The effect was retained at one-week follow up (Tables 1-2). These user study results suggest that the Playful Toothbrush system improves the tooth brushing skills of kindergarten children within a relatively short training period (*i.e.*, 5 consecutive days at approximately 5 minutes per day).

According to the occupational therapists involved in the study, most children found the learning process enjoyable. The occupational therapists also indicated that they could easily engage children in the brushing activity using the Playful Toothbrush system. However, whether the Playful Toothbrush system outperforms play-based occupational therapy without UbiComp technology requires further randomized control trials with larger sample sizes.

The adult therapist's presence during the user study may raise an issue that young children tend to enjoy performing well in front of an audience he/she cares about, therefore, may confound our user study result. However, whether a 6-year-old child brushes teeth properly or not is not just about motivation but related to capabilities. Even if a 6-year-old child is motivated to perform well in front of an audience, lacking proper brushing skill he/she still cannot perform well.

RELATED WORK

King *et al.* [17] described five persuasive strategies of adopting digital technology to change people's attitudes and behaviors. Among the five persuasive strategies, three are relevant to the proposed Playful Toothbrush system: simulated experience, surveillance and environment of discovery. Fogg [11], a pioneer in the field of Captology, the study of computer-based persuasion, proposed a functional triad for analyzing how people view or respond to computers: as tools, as media or as social actors. Different functions suggest different types of or designs for persuasive influence. An example relevant to the Playful Toothbrush system is "conditioning technology", which uses operant conditioning in computer games to reinforce target behaviors. Fogg *et al.* [12] further developed the concept of mobile persuasion which leverages the ubiquitous mobile phone as a platform for changing human behavior. Proposed examples of such a use were the MyFoodPhone [33] and the UbiFit Garden [8]. Some of the persuasive strategies of King *et al.* [17] and Fogg [11] were applied in the design presented here. Additionally, given the young age of the target users of the proposed system, playful aspects of persuasive technology are emphasized.

Several previous studies of persuasive technologies have targeted different behaviors and user groups: (1) tooth brushing behavior change, (2) general child behavior change and (3) general adult behavior change.

In the first category, Tooth Tunes [13] from Hasbro is a smart toothbrush designed to teach and encourage tooth brushing in young children. The toothbrush in the Tooth Tunes device is embedded with small pressure sensors which recognize brushing activity when the toothbrush is pressed against the teeth. When the sensors are activated, a two-minute music clip is played to encourage the user to brush for at least two minutes. The SmartGuide toothbrush from Oral-B [25] tracks and recognizes brushing in four different teeth quadrants. The brushing actions are counted on a simple display showing how much time a user has brushed or still needs to brush in each teeth quadrant. The Playful Toothbrush system differs from these systems in its increased precision of brushing recognition (*i.e.*, recognizing twenty-four teeth areas) and its interactive game design are based on a play-based occupational therapy model.

The second category targets behavioral change in children. The Playful Tray [20] targets mealtime behavior of young children. It embeds an interactive game played over a weight-sensitive tray surface, which can recognize natural eating actions of children. Child eating actions are then used as input in playing a racing game. To win the race, the child is motivated to eat. The Mug-Tree [18] is a playful mug that encourages children to develop a healthy habit of drinking water regularly. The mug contains a sensor which recognizes drinking action. These drinking actions are wirelessly transmitted to a digital photo frame running an interactive game. The game is based on a metaphor associating drinking water with periodically watering a virtual tree. As the child drinks water, the withering branches of the tree turn bright green. The SIDES [26] system is an assistive tool for training social cooperation skills in children with Asperger Syndrome. The system presents a four-player computer puzzle game played over a tabletop display. The puzzle game requires children to cooperatively build an optimal path enabling a virtual frog to travel from the lily pads. Improved team cooperation produces a more efficient path which receives more points. This game leverages the desire to play and win to effectively motivate children to learn and practice cooperative social skills.

The third category targets adult behavior change. Houston [7] is a mobile phone application that encourages physical activity by giving supportive comments and sharing with friends the number of steps taken during walking. Sharing of step counts and supportive comments provides social influence in persuading users to increase their daily step counts. ViTo (as opposed to TiVo) [22] is a persuasive TV remote control. This technology targets excessive TV watchers. By suggesting alternatives to TV watching, such as playing Non-Exercise Activity Thermogenesis (NEAT) games (*i.e.*, simple puzzles using physical activity as input), ViTo promotes increased physical activity and reduced television viewing time. Nutrition-aware Kitchen [4] is a smart kitchen that enhances traditional meal preparation and cooking processes by raising awareness of nutrition of food ingredients that go into a meal. The goal is to promote healthy cooking. The smart kitchen is augmented with sensors for detecting cooking activities and provides digital feedback regarding the nutritional value of food during preparation. Similarly, the Playful Toothbrush system adopts the approach of embedding a behavioral intervention into digital media or objects. However, the proposed approach also substantially differs from those above. Most significantly, the proposed approach employs play-based occupational therapy using persuasive technology to target young children. In this age group, play-based methods are the most effective means of solving behavioral problems. This work confirmed that UbiComp technology is a good match for occupational therapy because occupational therapy emphasizes readily observable and measurable changes in functional behavior. Because UbiComp technology can be deployed in the living environments of patients, real-time intervention in functional behaviors is possible.

CONTRIBUTION AND FUTURE WORK

This study proposed a Playful Toothbrush system using UbiComp technology to provide play-based occupational therapy for improving tooth brushing skills in kindergarten children. The design of the Playful Toothbrush digitally interfaces physical tooth brushing activity with a computer game to guide children in learning proper brushing techniques and to reinforce active participation of children in brushing activity. The user study results suggest that the Playful Toothbrush improves the tooth brushing skills of kindergarten children within a relatively short training period (*i.e.*, 5 consecutive days at approximately 5 minutes per day). After using the Playful Toothbrush for five consecutive days, kindergarten children exhibited significant improvement in effectiveness of teeth cleaning, increased number of brushing strokes, longer brushing time and more thorough brushing coverage in teeth areas.

The contribution is the integration of UbiComp technology with professional training to enhance training effect of children. The implication is that our UbiComp design principles have potentials for making many repetitive and complex developmental tasks attractive and simple to a child client.

Future studies may, based on input from parents and teachers, explore the use of UbiComp technology for many other developmental tasks in young children, from self-care behavior such as regular urinating, sleeping, dressing, etc., to learning proper social skills, all of which pose great challenges for parents and kindergarten teachers.

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