Toothbrush Training with a Videogame

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Research funded by the NIH National Institute for Dental and Craniofacial Research (1R43DE21334-1A1)
Abstract

Purpose
Improved toothbrushing technique can reduce the incidence of dental caries. An effective trainer must understand proper technique and commit prolonged close attention. Few adults can do both. Alternative training methods are sought. This study tests a videogame trainer with a sensor-enabled toothbrush.

Methods
Thirty-four children, age 5 and 6 brushed their teeth without any guidance. This performance was rated on nine metrics, and timed at each tooth surface. This assessment was repeated after seven, and after fourteen, nightly game play sessions. A control group was tested without playing the game.

Results
A blinded expert rated average improvement of 44% for the 7 Play treatment group and 78% for the 14 Play group, while scoring the control group improvement at 1%. Most p-values were below .001. Time on Tooth Surface charts display dramatic gains. Even a single game exposure improved performance.

Conclusions
A well-designed game with an instrumented toothbrush can improve young children's brushing behavior. They learn elements of Bass-Stillman technique and attend to previously neglected (e.g. lingual) surfaces. Toothbrush training often falls through a responsibility gap between parents and professionals. This tool can provide instruction, assessment and mentoring while strengthening the bond linking patient to practice.

Keywords
Toothbrushing, Dental Hygiene, Education of Patients
Introduction

Toothbrush Training Problem

Dental caries is pandemic in the modern world. It is the most widespread infectious disease\(^1\) in the United States, where over 21% of the population has untreated caries.\(^2\)

The fundamental prophylaxis for dental decay is removal of cariogenic biofilm,\(^3\) most often with a toothbrush. Proper brushing quickly removes debris and biofilm. Unskilled brushing is relatively ineffectual.\(^3\) Proper skills must be acquired by the developing child\(^4\) if caries are to be avoided. Unfortunately, few children enjoy access to adequate training.

Parental toothbrushing guidance is often uninformed or uncommitted.\(^5\) Professional instruction, when it is available at all, is necessarily brief and infrequent. The typical child grasps the brush in a fist\(^6\) and performs a crude horizontal scrub across clenched teeth, favoring the front teeth and those on the non-dominant side.\(^7\) Adults often overlook poor technique, preferring to monitor easily-observed behaviors such as regularity and duration.\(^8\) Many expect that childish scrubbing will yield to better technique as dexterity and cognition develop. In reality, bad habits persist,\(^9\) proving difficult to displace in later life.

Rather than address deficits in individual behavior, public health professionals generally devote resources to public avenues of prevention.\(^10\) Community water fluoridation,\(^11\) dental sealant programs,\(^12\) and access to corrective dentistry all mitigate the impact of poor dental hygiene,\(^13\) without addressing its cause.

Videogame Solution

The pleasure of play is rooted in skill mastery.\(^14\) While most games teach skills of little practical value (e.g. zombie killing)\(^15\), recent movements (Ben Sawyer’s Games for Health Summit\(^16\) and the White House’s Games For Impact,\(^17\)) promote game learning as a path to acquisition of critical knowledge and behaviors.

Skill acquisition requires repetitive practice with a closely attentive coach who maintains a high standard of performance.\(^18\) Only a few fortunate children will find a toothbrushing mentor with sufficient patience, perception and expertise. If a videogame can host a synthetic coach with these qualities, millions of children can benefit.

The Nintendo Wii, in 2006, introduced videogame players to wireless handheld sensors\(^19\) which can accurately measure orientation and motion. This technology enables a videogame to train high level toothbrush skills by precisely monitoring actual performance and matching these against an ideal.

Learning Objectives

The game is designed to teach five- and six-year-old children to brush their teeth using the methods separately advocated by brushing pioneers Bass and Stillman. This Modified Bass Stillman Technique (MBST) emphasizes gentle sulcus brushing interspersed with brief sweeps that roll the bristles from gumline to apex.\(^20\)

Although generally accepted as the ideal lifelong brushing technique for efficient cleaning,\(^21\) MBST is rarely taught to children perhaps due to concerns that its complexity and subtlety may exceed a child’s cognitive and fine motor skills.\(^24\) This study challenges that judgement. In particular, the operating hypothesis of this study is that the MBST is not too difficult for children to understand and perform. Rather, it may be too difficult for adults to teach.

The specific learning objectives included

Stroke Pattern: The player brushes along the gumline using extremely small strokes. After six strokes, the player performs a sweep. Rather than the traditional single sweep,\(^20\) this game teaches a more mnemonic
three-sweep rhythm.

Timing: Each tooth surface receives six tiny sulcus strokes and three quick sweeps. These are timed by the toothbrushing song which measures 7 seconds of brushing per surface.

Angulation The player places the bristles’ edge at the gumline, inclined 45 degrees. Slight pressure deflects bristles into the gingival sulcus.

Progression: The player learns a specific progression to ensure that no surface is neglected. This skill depends on children’s increased knowledge of the topology of their teeth beyond what is visible in the mirror.

Learning Methods

In a videogame, learning is achieved by addressing children through several media.

Terminology

“Incisor” and “molar” are not in a child’s vocabulary. But to guide the young player, the game must identify teeth. Childish English names replace scientific Latin. Like scientific names, they suggest functionality Each name refers to a pair of adjacent teeth. The central incisors are called “Biters”, the molars are “Chompers” and “Chewers” refers to the lateral incisor and canine. The upper and lower jaw each have only one set of Biters, but Chewers and Chompers exist on both the right and left sides.

The game replaced words like “lingual” and “buccal” with “inside” and “outside”. It avoids “Left” and “Right”. Few young children easily identify these.26,27 Also, the game accommodates handedness: left-handed children see a mirrored image, but hear the same words. Players start brushing on their non-dominant side, called the “across side”, and progress to the “near side”.

Visuals

The onscreen mentor emerged from several rounds of formative testing with children. An appealing ‘robot’ was selected for its design affordances. Robot geometry can be freely manipulated to facilitate demonstration, unconstrained by anatomy or physics.

No lips or cheeks obstruct view of the robot’s large teeth. His upper head floats above the lower jaw, entirely
detached. This resolves a particular limitation of the immature perceptual system. Children can lose situational awareness in the ‘tonsil’s view’ (camera inside the mouth, looking forward.)\textsuperscript{27} This robot has no structure in the back of his head. From behind, the mouth interior is clearly visible with an unobstructed view of lingual brushing.

![Unobstructed tonsil’s view of the robot’s mouth](image)

**Figure 2: Unobstructed tonsil’s view of the robot’s mouth**

**Music and Song**
The game teaches the child to measure time with a song. Its music is structured carefully. The tempo sets the pace of sulcus strokes and sweeps. The rhythm counts off twelve strokes and three sweeps for each tooth surface before advancing to the next surface. The song progresses through the mouth.

Its lyrics guide the player across the arc: start with Chompers, Chewers, then Biters, flip the brush, continue with Chewers, and end with Chompers. This process repeats across the lower jaw, and then, as the view shifts to the interior, the entire process repeats for lingual surfaces. Finally, occlusal surfaces are scrubbed in each quadrant.

**Sensors**
The toothbrush incorporates an Inertial Measurement Unit (IMU), a package of gyroscopes and accelerometers. Readings from these sensors allow the software to continuously calculate the orientation of the toothbrush and infer its position in the mouth. The software directly reads the torque applied by sweeping motions, and can calculate brushing force as the child accelerates the brush back and forth. Eigendecomposition projects data from the coordinate system of the brush to the axes of motion and gravity.

**Score**
*Brush Up* belongs to the game genre known as ‘rhythm game’ or ‘beat-match.’ This genre includes popular music performance games like *Guitar Hero*, *Rock Band* or the classic *Dance Dance Revolution*. The player follows an onscreen exemplar who performs the desired activity in time with the music. The player is rewarded for accurate conformance with the demonstration. Performance errors are detected by the game system and immediately highlighted by verbal, visual and sound effect cues in addition to a scoreboard.
penalty. The player is congratulated when these errors are later corrected.

**Methods**

The studied intervention consisted of nightly unsupervised play of the game in the subject’s home. Before and after intervention, subjects brushed their teeth in the laboratory, where their performances were videotaped, timed and scored.

Thirty-four subjects completed the trial. Parents of five- and six-year-olds were recruited in transitional neighborhoods with mixed socio-economics, education and ethnicity. The pool was 47% Caucasian, 38% African-American with the remainder Asian, Hispanic, multiple race and other. 17% were left-handed. Two pairs of siblings participated, playing with separate accounts on the same game computer.

On completion, each family received $200. No partial payment was available for incomplete participation. Only one participant failed to complete the study, because the family had no internet connectivity, required for nightly automated reports that verify compliance with study protocol.

The Morehouse School of Medicine Institutional Review Board for Social and Behavioral Studies reviewed the experimental protocol, subject material and the safety and privacy monitoring plans.

The parental informed consent document explained the trial in plain English (second grade reading level). Furthermore, the intake researcher obtained verbal assent from each child, after explaining the study using the approved age-appropriate script.

Subjects were surveyed for demographics, dental history and gameplay experience. Their baseline toothbrushing performance was observed and recorded. The subjects are randomly assigned to a control or treatment group. Except the control group, subjects then played the game in the laboratory, minimally guided by a research assistant. Parents were instructed to set up the game at home, and to ensure that the child played nightly. However they refrained from any toothbrushing instruction during the trial and from helping the child interpret game content.

![Figure 3: A child playing the game in the laboratory](image)

Each family in a treatment group left the laboratory with a sensor-enabled toothbrush and a laptop computer with the game installed. It had bluetooth connectivity to the toothbrush and internet connectivity to
GamesThatWork servers.

At home, each child played the game nightly for a week. Many continued for two weeks. At the end of treatment, researchers again observed the child’s unguided toothbrush performance. The equipment was returned, and the stipend paid. Equipment was cleaned and a new brush head installed. Trial sessions were staggered so 12 laptops could serve 34 participants.

Each subject was issued two identifiers. Participant ID tracked consent, nightly treatment compliance, possession of study equipment and payment. Subject ID collected anonymized demographic information and performance data. The key correlating these two identifiers was handwritten and held by the Data and Safety Monitor.

Physical safety measures included foodsafe attachment of brush heads to Wiimote sensors, and infection control procedures directed by an experienced hygienist.

The experiment relied on multiple observations of unguided toothbrush performance by each subject.

- Pre-intervention: All 34 subjects were measured before intervention as a baseline for improvement.
- 0 Play: Five subjects were tested after a week without treatment. This group was used only to test for the Hawthorne Effect (Observation alone can improve performance). This subject pool was representative of the overall treatment when measured by their performance on initial test. These Hawthorn Effect control subjects then served in subsequent treatment groups.
- 1 Play: Five subjects played the game exactly once and were tested after a week with no further exposure to the game or other reinforcement. This group provides a formative test of the effect of a single exposure to the game. They also served in subsequent treatment groups.
- 7 Plays: All 34 subjects were tested after playing the game daily for a week. Some had served previously in the Control Group. Others continued as members of the 14-Play treatment Group.
- 14 Plays: Fifteen subjects played for two weeks to test dose dependency.

Toothbrushing was performed in a GamesThatWork laboratory decorated as a bathroom environment with a sink and mirror. There was no brushing guidance from any adult, peer, video, game, music or clock. A friendly researcher in a lab coat instructed the subject, observed brushing and interviewed the subject. An assistant remotely recorded the performance. Parents could observe only through a small window.

Except for dropping one family without internet, and the fortuitous emergence of a single-exposure treatment group, there were few deviations from protocol. The early-stage videogame, the prototype toothbrushes and remote data collection functioned well. Parents reported that children enjoyed the game. A researcher providing technical support observed a child crying when the game was briefly unavailable.

The experiment relied on two distinct metrics for toothbrush performance.

**Performance Ratings**

In the laboratory, a trained dental hygiene researcher observed performance, blinded to control or treatment group assignment. She enumerated errors in nine skill dimensions:

- Patience: Subject completes each brushing surface.
- Moderation: Subject avoids excessive force
- Brush Position: Subject holds brush at 45 degree angle near gumline
- Variation: Subject performs distinct sulcus and sweep strokes
- Sweeps: Subject sweeps from gumline to apex
- Restraint: Subject performs small horizontal sulcus stroke
- Tooth Group Awareness: Subject focuses on each surface
- Surfaces: Subject attends to all classes of tooth surfaces
Orderly Progression: Subject brushes teeth in sequence

Time on Tooth Surface (ToTS)

Time On Tooth Surface (ToTS) measurements were based on video analysis performed retrospectively by a trained research assistant blinded to treatment group assignment and sampling schedule. ToTS is an objective time measurement subject to third party review. Using electronic timers and video analysis software, the researcher measured brush time on each of 16 surfaces. These 16 surfaces did not match the 24 brushing surfaces taught in the game, but they could be reliably observed in video analysis. Total accumulated time on each surface was not necessarily contiguous, since children do not always brush in orderly sequence.

Results

Performance Ratings

The blinded expert hygienist scored each brush performance with an error count for each of nine metrics. The initial pre-test provided a baseline. Subsequent scores reflected error reduction from the baseline, normalized so 0 marks no improvement and 1.0 indicates error-free performance.

![Figure 4: Performance improves with number of plays](p-values: *=0.050   ** <= 0.005   *** <= 0.001 )

Paired t-tests produced p-values for each measure. However, the 14-Play group sample size is too small to support assumptions required for this method. In that group, p-values are based on paired Wilcoxon signed rank tests.

Time on Tooth Surface (ToTS)
Figure 5: Improvement of Time On Tooth Surface with number of plays

This chart bisects the mouth (Upper, Lower) and trisects each half (Left, Front, Right). Each segment indicates brushing time on buccal, lingual and (except in Front) occlusal surfaces. Radial bands mark 2.5 seconds of brushing. Three bands radiate outward (buccal), inward (lingual) and across (occlusal). Achievement of the 7.5 second training goal fills all three bands.
These histograms demonstrate the distribution of ToTS score within the baseline Pretest and each of the treatment group results.

This scatter chart indicates four points on the response curve that show TOTS improvement from the baseline corresponding to no exposure (−.02), single exposure (.11), one week (.18) and two weeks (.42) of nightly play.
Discussion

Performance Ratings

A week after the pre-test, during which the Control group showed no improvement, the single play group improved 24%, and the 7 Play group averaged 44%. After 14 days this improvement grew to 78%. These results clearly indicate efficacy and exhibit sharp dose dependency. The saturation dose is not determined.

The null hypothesis, that these results are random artifacts rather than evidence of actual learning, is not supported by statistical evidence. Almost all results of the 7-play group and several 14-play results have p-values below .001. The chance of any of these being a random artifact is less than one in a thousand.

Observations made by an experienced dental hygiene researcher established the score. Expert ratings always risk unconscious bias. Blinding the researcher to control or treatment group membership mitigates confirmation bias and measures scoring reliability. The scores show highly significant differences between each treatment group and the baseline. Control group scores exhibit little change from the baseline. This suggests that the blinded researcher performed repeatable assessments.

Time on Tooth Surface (ToTS)

The ToTS charts above demonstrate the measured toothbrushing patterns as they improve with increasing exposure to the game. Naive children (0 Plays) brush their front teeth and the buccal surface, particularly the more comfortable non-dominant side. Cursory attention is paid to other buccal surfaces and the occlusal surfaces that are easiest to brush–those on the lower jaw and especially the non-dominant side. The complete neglect of all lingual surfaces is obvious.

Charts of the control group are indistinguishable from the baseline.

One exposure (1 Play) left children with modest improvement, but introduced them to the lingual surfaces. Subjects still brushed these surfaces when observed, a full week after the single game exposure.

After one week (7 Plays), brushing time was distributed far more uniformly across all surfaces, although front teeth dominate and lingual surfaces are underbrushed.

After two weeks (14 Plays) attention to the surfaces is fairly even, and generally sufficient. Some areas still pose problems. The occlusal surfaces of the upper teeth, especially on the nondominant side, are difficult to brush, as is the inside surface of the front teeth. Deficits in the lower lingual surfaces may demonstrate interference by the tongue.

All improvements in ToTS are statistically significance (p-value <.05), except for those measures where baseline ToTS was already very high (e.g. incisors, and non-dominant side buccal surfaces) allowing no room for improvement.

Unlike performance ratings, which depend on expert judgement, ToTS is objectively measured by timing video clips. ToTS scores are reproducible and subject to third party review. Scoring is retrospective, and the researcher can be well blinded. Cognitive bias is not an important risk.

Conclusions

The game had a sharp positive effect on behavior. Large, statistically significant improvements were recorded across the thirty three different measures that tracked the game’s learning objectives. These metrics include both expert scoring and objective time measurements.

In pre-intervention testing, all subjects neglected all lingual tooth surfaces. By playing the game, they
discovered the interior of their mouths. Subsequently, they demonstrated the learned behavior of brushing the lingual surfaces.

All learning measures exhibit dose dependency: more gameplay means more improvement of behavior. Fourteen plays resulted in better performance than seven, but even a single instance of playing the game induced measurable improvements.

Further studies will investigate skill retention, dose dependence, and instructional refinements such as avoidance of the tongue, and more.

Practice

A game that teaches toothbrush technique serves an important role in dental practice. Few parents can teach toothbrush technique\textsuperscript{5}. Many rely on dental professionals.

However, oral hygiene instruction (ADA code 1330) is infrequently covered by insurance and never sufficiently. Skill acquisition relies on repetitive practice and an attentive coach\textsuperscript{18} - not three minutes every six months. By providing in-home game-based training, the dentist rescues patients from a responsibility gap between parents, practice and payers.

The game can remotely report home brushing behavior including regularity, duration and specific areas of deficiency. Deficiency can trigger timely messages to the family via digital media and to the practice, so that the hygienist can focus instruction where the child needs it most.

Brush Up is designed to support, not supplant, hygienist education and to strengthen bonds between patient and practice. By featuring the face and voice of a child's own practitioner, the game aims to reduce anxiety and develop positive anticipation of upcoming appointments.

Acknowledgments

Research was directed by Joyce Flores and conducted by Brian Daviadoff with formative testing by Leontyne Robinson. Traci Leong performed statistical analyses. Stella Lourenco represented the child’s perspective during experiment design and analysis. Robert Jacobson represented that of the clinician. Game art and animation were led by Stephanie Chergi and executed by Jenna DiLorenzo. Vernon Simms produced the music. Software was directed by Jesse Jacobson and engineered by Hilario Gonzalez and Adam Gensler. Daniel Fuller prepared this document. Dov Jacobson initiated and led the project. (Robert, Dov and Jesse Jacobson are grandfather, father and son.)

Funding is provided by National Institutes of Health, National Institute for Dental and Craniofacial Research.

Author Disclosure Statement

Several authors are principals and employees at GamesThatWork. This studio initiated the Brush Up game and has an ongoing interest in its success.
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