A Multisensory Interactive System for Real-Time Bodyweight Exercise Feedback

Combining IMU Sensors with Intelligent Audio-Visual Feedback

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Multisensory interactive systems course
held by Luca Turchet

Project Overview

Multi-modal Feedback

Visual + Audio

Real-time Processing

<50ms latency sensor-to-display

Target Application

Physical therapy and exercise training

IMU Sensors (BNO055 + ADXL337) →**Teensy Microcontroller** →**Flask Web Server** → **Real-time Web Interface**

System Components

Hardware Stack

- **Teensy 3.6**: ARM Cortex-M4 microcontroller
- **BNO055**: 9-axis IMU with sensor fusion
- **ADXL337**: 3-axis analog accelerometer
- **Raspberry Pi**: Web server host

Software Stack

- **Embedded**: C++ with advanced filtering
- **Backend**: Python Flask + SocketIO
- **Frontend**: JavaScript + Web Audio API
- **Communication**: Serial → WebSocket pipeline

The Challenge

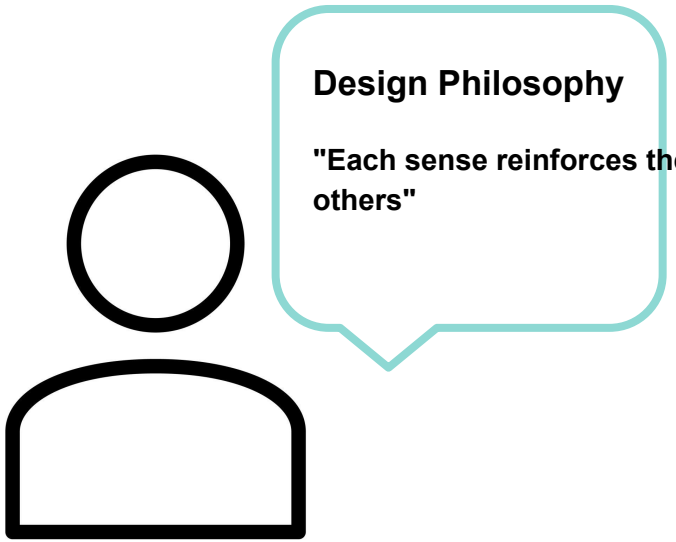
Traditional Exercise Feedback Limitations

- Visual-only interfaces require constant attention to screen.
- Generic audio cues lack exercise-specific meaning.
- Delayed feedback reduces effectiveness.
- Single-modal systems miss learning opportunities.

My Solution

Scientifically-designed multimodal feedback that guides users through exercise phases using coordinated audio-visual cues.

Multimodal Feedback System - Overview



The Feedback Loop

1. **Sensor Data** → Real-time position detection
2. **State Machine** → Exercise phase recognition
3. **Multimodal Output** → Synchronized audio + visual
4. **User Response** → Improved exercise performance

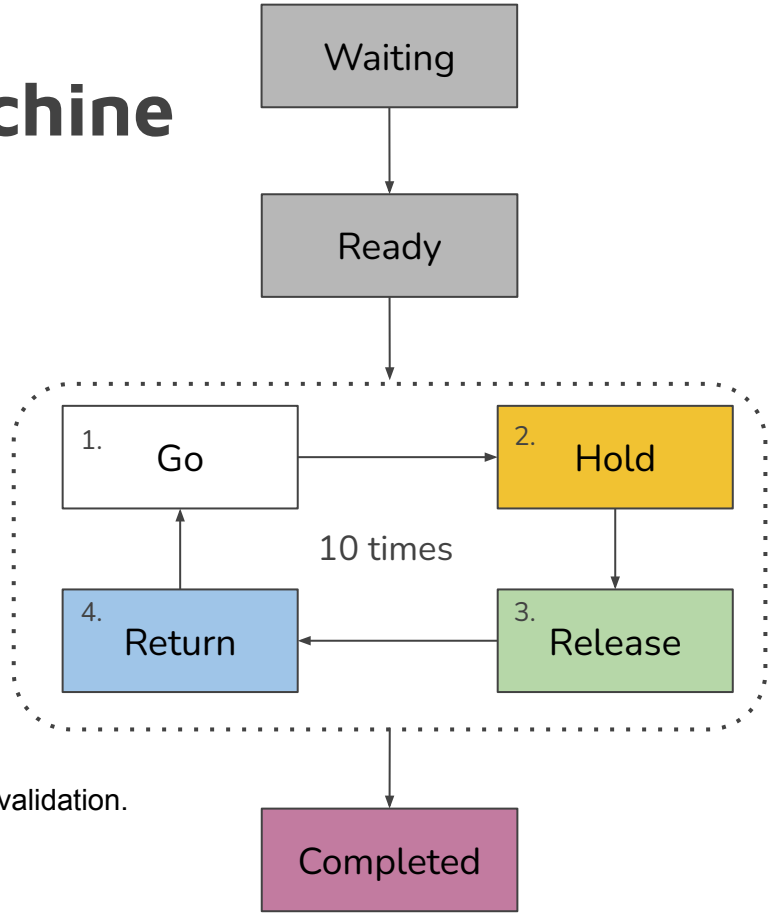
Scientific Foundation

Based on **dual coding theory** and **multisensory integration** research.

Exercise Phase State Machine

Seven Distinct Phases

1. **WAITING** → System initialization
2. **READY** → Prepare for movement
3. **GO** → Begin movement to target
4. **HOLD** → Maintain target position
5. **RELEASE** → Movement completed successfully
6. **RETURN** → Return to starting position
7. **COMPLETED** → Exercise completed



State Transitions

Data-driven transitions based on real-time sensor input with temporal validation.

Color Psychology in Exercise Feedback

Scientific Color Selection

WAITING/READY: Gray/Light Gray

Psychology: Neutral, non-stimulating, preparation state

Reference: Color psychology in UI design (Nielsen Norman Group)

GO: Clean white

Psychology: Purity, new beginning, clarity of action

Reference: White space psychology in design (Gestalt principles)

HOLD: Yellow/Orange Gradient

Psychology: **Alert colors** that maintain attention without stress

Reference: Traffic psychology - yellow = caution/attention (FHWA standards)

Color Psychology (continued)

RELEASE: Green Gradient

Psychology: Universal **success** and **completion** signal

Cross-cultural: Green = positive across most cultures

Reference: Color symbolism research (Berlin & Kay, 1969)

RETURN: Blue/Cyan

Psychology: **Calming transition**, controlled movement

Reference: Blue psychology effects (University of Rochester studies)

COMPLETED: Purple/Magenta

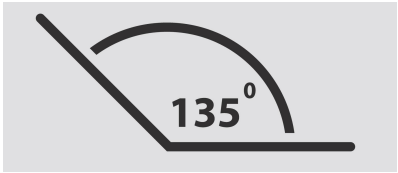
Psychology: **Achievement**, **premium** experience

Reference: Purple in gamification psychology (Deterding et al.)

Gradient Design Strategy

Why Diagonal Gradients?

135-degree angle - Psychologically optimal direction



Design Benefits

- **Visual depth** without distraction from core message
- **Dynamic feel** while maintaining readability
- **Natural eye movement** following gradient flow
- **Modern aesthetic** that feels professional yet engaging

Reference

Gradient psychology in modern web design (Smashing Magazine, 2019)

Psychoacoustic Sound Design - Hold Sound

Hold Sound: 880Hz → 440Hz Sweep

Purpose: Signal target position reached, maintain attention

Frequency Selection

- **880Hz (A5)**: **Attention-grabbing** high frequency
- **440Hz (A4)**: **Relaxing** settling frequency
- **Octave relationship**: Naturally harmonious progression

Acoustic Psychology

- **Descending sweep**: Suggests "settling" into position
- **400ms duration**: Long enough to notice, short enough to not annoy
- **Sine wave**: Pure, non-aggressive tone suitable for repetition

Reference: *Psychoacoustics: Facts and Models* (Zwicker & Fastl, 2007)

Psychoacoustic Sound Design - Release Sound

Release Sound: 659Hz → 523Hz Double Beep

Purpose: Celebrate successful hold completion

Musical Design

- **659Hz (E5) → 523Hz (C5)**: **Descending major third**
- **Double beep pattern**: Distinctive from hold sound
- **Triangle wave**: Richer harmonics for celebration feel

Psychological Effect

- **Descending pattern**: Suggests "release/let go"
- **150ms spacing**: Recognizable rhythm pattern
- **Major interval**: Positive emotional association

Reference: *The Psychology of Music* (Deutsch, 2013)

Psychoacoustic Sound Design - Success Fanfare

Completion Sound: C Major Arpeggio

Purpose: Celebrate full exercise completion

Musical Structure

- **523Hz, 659Hz, 784Hz, 1047Hz**: C-E-G-C octave
- **Ascending arpeggio**: Classic "success" musical pattern
- **200ms staggered timing**: Builds excitement

Cultural References

- **Video game achievements**: Universally recognized success sound
- **Major triad psychology**: Happiness and resolution
- **Rising pitch**: Associated with progress and accomplishment

Reference: *Music, Cognition, and Computerized Sound* (Cook, 1999)

Web Audio API Technical Innovation

Why Not Audio Files?

Traditional approach limitations:

- Network latency for file loading
- Limited customization
- Bandwidth requirements
- Caching issues

My Approach: Real-time Synthesis

- **Zero latency**: Generated in browser
- **Perfect timing**: Synchronized with visual feedback
- **Customizable**: Every parameter controllable
- **Lightweight**: No additional downloads

Technical Achievement

Cross-browser audio synthesis with automatic fallbacks and user gesture handling.

Multimodal Synchronization

Precise Timing Coordination

Challenge: Synchronize visual transitions with audio cues within human perception limits

My Solution

- **Web Audio API timing**: Sample-accurate scheduling
- **CSS transition timing**: Matched to audio envelope
- **State machine coordination**: Single source of truth
- **<20ms synchronization**: Below human detection threshold

Result

Seamless multimodal experience where audio and visual feel naturally connected.

Visual Animation System

Strategic Animation Choices

Pulse Animation: 2-second cycle

- **Scientific basis**: Matches resting respiratory rate
- **Psychological effect**: Calming, rhythmic presence
- **5% scale change**: Noticeable without being distracting

Flash Animation: Success feedback

- **0.5-second triple flash**: Attention-grabbing celebration
- **Opacity modulation**: Less aggressive than color flashing
- **Timed with audio**: Reinforces success moment

Typography and Hierarchy

Information Architecture

Primary: 8rem main text **Immediate status recognition**

Secondary: 2rem sub text - **Context and instruction**

Contextual: 3rem rep counter - **Progress tracking**

System: 1rem status indicators - **Technical information**

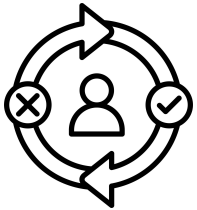
Font Selection: Arial Black

- **Maximum impact**: High weight for visibility
- **Universal availability**: No loading delays

User Experience Impact

Multimodal Learning Benefits

- **Faster skill acquisition**: Multiple sensory pathways
- **Better retention**: Reinforced memory formation
- **Reduced cognitive load**: Intuitive feedback system
- **Enhanced motivation**: Gamification through sound/color



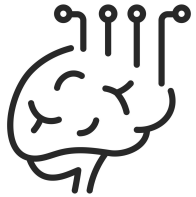
Clinical Applications

- **Physical therapy**: Objective progress tracking
- **Exercise compliance**: Immediate feedback encourages proper form
- **Remote monitoring**: Therapists can observe virtually
- **Accessibility**: Supports users with various impairments

Technical Innovation Summary

Novel Contributions

1. **Psychoacoustically-designed** exercise audio feedback
2. **Evidence-based color psychology** for exercise states
3. **Real-time sensor-to-browser** multimodal pipeline
4. **Cross-platform web audio** synthesis system



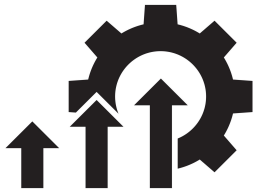
Beyond Traditional Approaches

- **Scientific foundation**: Based on perception research
- **Technical excellence**: High-performance real-time system
- **User-centered design**: Addresses real clinical needs

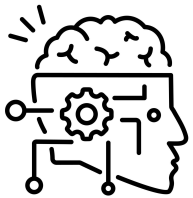
Future Enhancements

Immediate Improvements

- **Personalized audio profiles**: User-customizable tones
- **Adaptive difficulty**: Feedback based on performance
- **Exercise library**: Multiple movement patterns
- **Data analytics**: Long-term progress tracking



Advanced Research Directions



- **Machine learning**: Predictive feedback systems
- **Spatial audio**: 3D sound positioning cues
- **Haptic integration**: Tactile feedback addition
- **Clinical validation**: Formal efficacy studies

Lessons Learned

Technical Insights

IMU sensor reading require proper management of raw values and applied processing.

Real-time systems demand robust error handling and recovery.

Multimodal design requires deep understanding of human perception.

Design Insights

Scientific backing elevates user experience design.

Accessibility considerations improve system for everyone.

Performance optimization is critical for real-time applications.

Conclusions

Project Achievements

- ✓ **Functional multimodal feedback system** with <50ms latency
- ✓ **Scientifically-designed audio/visual cues** based on psychology research
- ✓ **Cross-platform web application** with accessibility compliance
- ✓ **Real-time sensor integration** with robust error handling

Key Innovation

Evidence-based multimodal design that transforms exercise feedback from generic beeps and flashes into **meaningful, scientifically-optimized sensory experiences.**

Questions & Discussion

Contact & Code

- **GitHub Repository**: Multisensory-Interactive-System-project
- **Live Demo**: shared video in Google Drive
- **Technical Documentation**: Refer to project README files

Thank You!

References

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