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Supplementary Materials for

Robotic reading companions can mitigate oral reading anxiety in children

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The PDF file includes:

Materials and Methods
Figs. S1 to S3

Other Supplementary Material for this manuscript includes the following:

MDAR Reproducibility Checklist

SUPPLEMENTARY MATERIALS AND METHODS

Reading Tablet Application

We developed a dedicated Android tablet application, as seen in Fig. S3, containing the texts used for this study which had a separate mode for both the human and the robot reading companions. We used two tablets during the study, one for the participant and one for the companion. One tablet ran the application while the other tablet was mirrored, so that both the participating child and the reading companion saw the same text. While the human researcher was being read to, they held the tablet that controlled the progression of the pages and allowed them to select each word that the child mispronounced. After the child had completed the page, the researcher could press a button indicating they were done, which would cause three words, either selected by the researcher or pre-selected vocabulary words, to highlight on the page. After the child re-read the highlighted words, the researcher could press another button to proceed to the next page. While the robot was the reading companion, the child held the tablet that controlled the progression of the pages. In this mode, the child was unable to select words to be highlighted. The other tablet was propped in front of the robot where the robot could appear to be reading along with the child. The child was instructed to press a "done" button when they had finished reading the page, which would trigger the robot to ask the child to repeat the three highlighted words. After the child had repeated the words, they could press the "next page" button to continue. After the "'done" button was selected, there was a five second lock-out on the "next page" button to ensure children didn't accidentally click through the interaction without following the instructions to repeat words. In both reading with the robot and with the human, the child was ultimately in charge of the pace of reading at all times during the study either by directly controlling the buttons or by the researcher advancing pages after the child verbally indicated they were ready to proceed, attempted to press the button on their own tablet, or paused long enough to indicate they were finished.

Passages and Vocabulary Words

Passages read by children during this study were taken from the Dynamic Indicators of Basic Early Literacy Skills (DIBELS) 8th Edition 7th and 8th grade benchmark oral reading fluency passages (https://dibels.uoregon.edu/materials/dibels). For the baseline session, children read the story "Coyotes and Wolves" aloud by themselves. In the first session with a companion, children read the passages "Fizzy Water" and "Government". In the second session, children read the passages "Prize Winning Vegetables" and "Crows". In the sessions with companions, three vocabulary words per page, or nine total words per passage, were pre-identified based off of pilot testing with the passages. When children did not mispronounce any words on a page, they were asked to repeat the three vocabulary words for that page.

"Fizzy Water"

selected vocabulary words were: seltzer, dioxide, pharmacists, regardless, promoted, strength, associated, ale, and increased.

"Government"

selected vocabulary words were: instances, basis, arise, aristocratic, coup, totalitarian, democracies, anarchy, and proponents.

"Prize Winning Vegetables"

selected vocabulary words were: renowned, neighbors, flourish, enormous, zucchini, calf, manageable, asteroid, and extraterrestrial.

"Crows"

selected vocabulary words were: devour, associated, sociable, astonishingly, congregate, ornithologists, intelligence, avian, and intersections.

Correction Algorithm

We wanted both the human and the robot to be capable of identifying when a participating child had mispronounced a word in order to provide corrective feedback, intending to enhance their learning. While the human reading companion could manually select missed words, the robot reading companion used speech recognition and a correction algorithm. We used Amazon Transcribe as our speech recognition service to transcribe the audio from participating children as they read aloud which was compared to the passages being read. When a mismatch occurred between a recognized word and the expected word in the passage, we used a Double Metaphone phonetic algorithm (*61*) to convert both the recognized word and the expected word into approximated phonetic codes. We then used the Levenshtein edit difference (*62*) between the phonetic code of the recognized word and expected word to determine if the child truly made an error or if the speech recognition may have mis-identified a word the child likely pronounced correctly. Although this method is neither as sensitive nor as accurate as a human, it was still capable of handling obvious mispronunciations, ensuring children received corrective feedback on many of their errors. In the event that children mispronounced more than three words on a single page, they were asked to repeat a random selection of three of the missed words. If they mispronounced less than three words, the list of three was supplemented with a random non-overlapping selection from the vocabulary words.

Physiological Sensors

Each physiological measure had a dedicated sensor. To record participant audio, we used a Logitech Blue Snowball iCE USB microphone placed approximately 1-2 feet away from the participant. Audio files were recorded in .wav format using the arecord function in Linux. To measure heart rate we used a CooSpo Armband Heart Rate Monitor, an optical heart rate sensor worn on the participant's arm. The wearer's heart rate in beats per minute (BPM) was recorded in one-second intervals through the Strava application.To record thermal videos of participants we used a TOPDON TC001 Thermal Imaging Camera with 256x192 IR Resolution. The camera was run using the TCView app on a Windows laptop.

Thermal Data Analysis

The TC001 thermal camera was chosen due to being low-cost and highly portable. The resolution (256x192) was deemed sufficient for our analysis as it exceeds the resolution of cameras used for similar facial region of interest tracking during thermal analyses (*77*). As the TC001 does not export a temperature matrix, we developed a process for calculating the temperature for each pixel using the video color map and the maximum and minimum temperatures which the camera automatically annotates. The color map used in the TCView application (the dedicated Windows application used to run the camera) is a sequential color map, so we mapped the images to grayscale to preserve luminance values. Then, because both color scales are monotonically increasing in luminance, we could linearly interpolate between the grayscale values of the colors on the two ends of the color scale to get the temperatures at any given pixel in the image. However, we noticed that the endpoints of the color scale had slight differences between frames. Thus, we sampled six frames and averaged their lightest and darkest grayscale values and interpolated between those values (35 and 212.5, respectively) instead of interpolating between the grayscale values at the two ends of the color map. It is by this method that we determined this formula to find the temperature at any pixel:

$$T_p = T_{min} + \frac{(g - 35.0)}{(212.5 - 35)} * (T_{max} - T_{min}) \tag{1}$$

where T_p is the temperature at at pixel p, g is the grayscale value at the pixel, T_{min} is the minimum temperature in the frame and T_{max} is the maximum temperature in the frame.

Comprehension Tests

Fizzy Water

1. What gives soda water its carbonation?
   (a) Oxygen
   (b) Nitrogen
   (c) Hydrogen
   (d) Carbon dioxide
2. In the past, why was soda water sold at pharmacies?
   (a) It was believed to have health benefits.
   (b) It was used as a remedy for various health problems.
   (c) It was mixed with other drugs for patients.
   (d) All of the above.
3. What was one of the first best-selling flavors of soda?
   (a) Lime
   (b) Cherry
   (c) Coffee
   (d) Dr. Pepper
4. Why did cola companies start making diet versions of their soda?
   (a) To promote health benefits
   (b) To reduce sugar content
   (c) To increase popularity
   (d) To improve taste
5. What are some healthier drink alternatives mentioned in the passage?
   (a) Tea and unflavored soda water
   (b) Tea and coffee
   (c) Juice and flavored soda water
   (d) Milk and energy drinks

Government

1. What is the defining characteristic of an aristocratic government?
    (a) Absolute power in the hands of a single person
    (b) Power shared among the general population
    (c) Power and control in the hands of a few individuals
    (d) Direct involvement of citizens in decision making
2. How do despotic rulers often come to power?
    (a) Through military coups
    (b) By inheriting power from relatives
    (c) Through elections and campaigns
    (d) Either a or b
3. What is the main difference between direct democracy and indirect democracy?
    (a) In direct democracy citizens elect politicians.
    (b) In indirect democracy citizens are involved in decision making.
    (c) Direct democracy relies on majority rule.
    (d) Indirect democracy gives equal power to all citizens.
4. What is one disadvantage of a simple majority system in democracies?
    (a) It can lead to power being concentrated in the hands of a few.
    (b) It can hinder the decision-making process.
    (c) It often ignores the desires of the people.
    (d) It can disadvantage those with minority viewpoints.
5. What is the defining characteristic of anarchy?
    (a) Absolute power in the hands of a single person
    (b) Power shared among the general population
    (c) Lack of any controlling body or government
    (d) Direct involvement of citizens in decision making

Prize Winning Vegetables

1. What made Bradford and Marianne's tomatoes special compared to those grown by their neighbors?

   (a) They used special seeds.

   (b) They sprayed their plants with a secret chemical formula.

   (c) Bradford's fiddle-playing on moonlit nights.

   (d) They had a secret method that only they knew.

2. What did Marianne discover in the garden at the end of August?

   (a) A giant pumpkin

   (b) A hidden zucchini

   (c) A newborn baby

   (d) An enormous tomato

3. Why did Marianne convince Bradford to leave the zucchini on the vine a little bit longer?

   (a) To see how big it would grow

   (b) To allow it to ripen fully

   (c) To show it off to their neighbors

   (d) To win a gardening contest

4. How did Marianne preserve some of the zucchini?

   (a) She cooked some slivers in oil.

   (b) She made zucchini bread from the pulp.

   (c) She stored it in a wood chipper.

   (d) She sold it to the neighbors.

5. What is the narrator's theory about the garden's success?

   (a) Luck and coincidence

   (b) Bradford's fiddle-playing

   (c) Extraterrestrial minerals from an asteroid

   (d) Special soil and nutrients

Crows

1. What types of food do crows eat?
    (a) Only vegetables and fruit
    (b) Only nuts and seeds
    (c) Only insects and smaller birds
    (d) A variety of food, including carrion and small animals
2. What is one reason ancient people associated crows with death?
    (a) Crows are scavengers and eat carrion.
    (b) Crows migrate during the fall and winter.
    (c) Crows live in large family groups.
    (d) Crows execute acrobatic back-flips in flight.
3. What is the purpose of crows gathering in large roosts?
    (a) To play games and socialize with other crows.
    (b) To find food and protect against predators.
    (c) To build nests and raise their young.
    (d) To migrate to different locations together.
4. How do crows demonstrate their intelligence?
    (a) By gathering in large groups for protection.
    (b) By dropping nuts onto roads to crack them open.
    (c) By communicating with each other in roosts.
    (d) By migrating to different regions for food.
5. What is a unique behavior of crows in Japan?
    (a) They drop walnuts at intersections for cars to crush.
    (b) They perform acrobatic backflips in flight.
    (c) They use tools to poke for grubs in the ground.
    (d) They communicate and exchange information in roosts.

Supplementary Figures

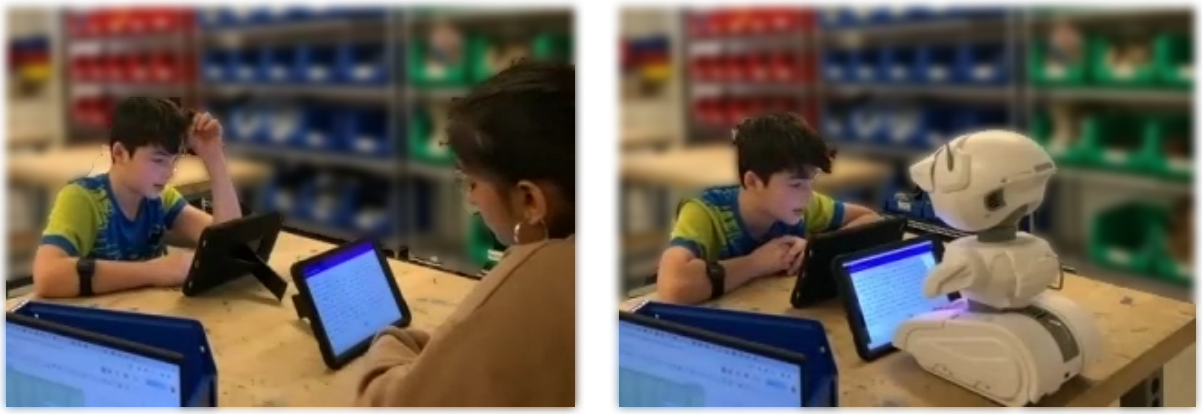

Figure S1: Study Setup. (**A**) Participant reading out loud to the human. An optical heart rate monitor is on his forearm. To the right of the participant is a microphone and the thermal camera. (**B**) The same participant reading to the robot, all elements of the setup besides the reading companion remain the same.

Figure S2: Thermal Images. We analyzed participants' facial temperature in the periorbital region (the area surrounding the eye) as a measure of anxiety. After identifying the periorbital region using the yolov5l_face model (*74*), we took the average temperature of the 10% hottest pixels.

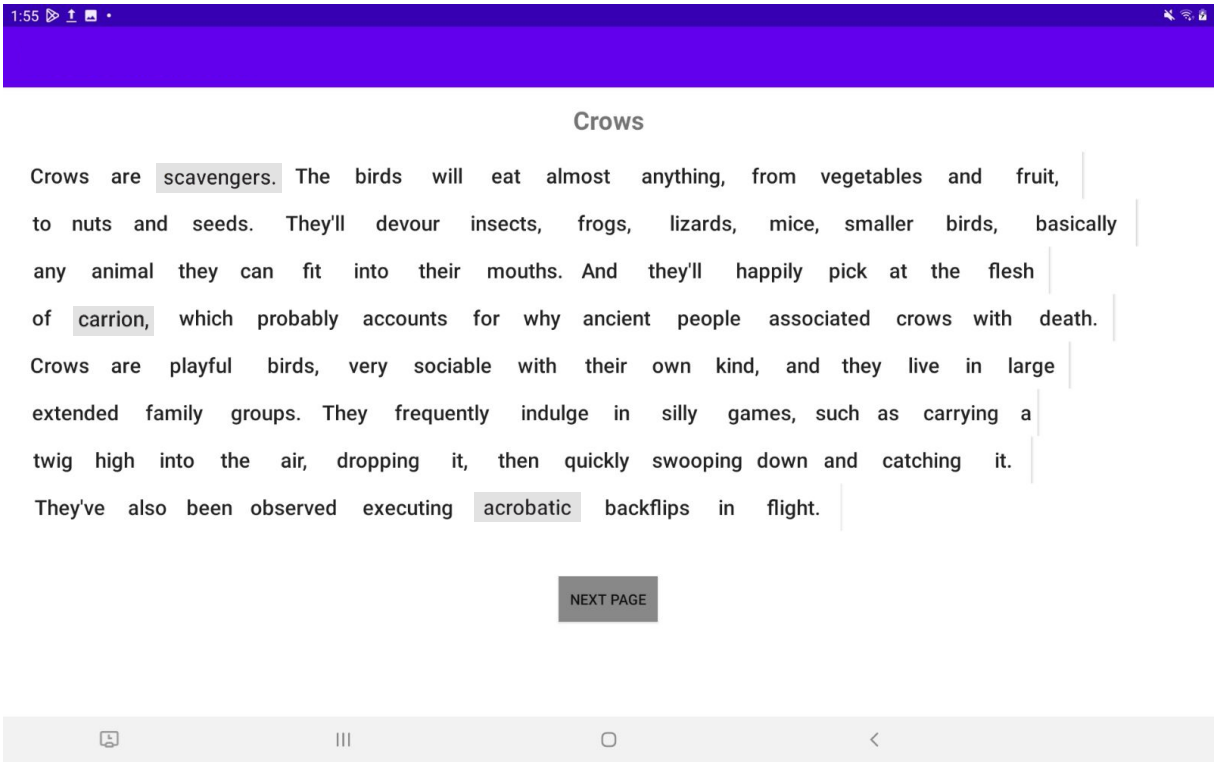

Figure S3: Reading Application. A screenshot of the reading application developed for this project. Three words on this page are highlighted, indicating the child should repeat them before proceeding to the next page.