Robot-Assisted Language Education and Speech Therapy for Children with Cleft Lip and Palate

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Abstract: Cleft lip and palate (CLP) is a congenital anomaly that can have detrimental effects on an individual's ability to produce certain sounds, including bilabial sounds such as /m/ and alveolar sounds such as /n/, as well as sounds that require closure between the nasal and oral cavities, such as sounds ending in /-ɪŋ/. While surgical intervention can assist in correcting anatomical irregularities, consistent speech and language therapy sessions are often necessary to overcome obstacles associated with speech production. The research problem addressed in this study is the interruption of regular therapy, as evidenced by the discontinuation of services during the COVID-19 pandemic, which can lead to setbacks in progress and an increase in the risk of developmental delays in children. To explore the potential of educational robots to address this problem, this paper (i) investigates the user requirements, usability considerations, and attitudes to speech therapy robots, from the perspective of parents and carers of children with CLP, (ii) presents an experimental prototype for CLP language education and speech therapy using a humanoid robot, named Robot Lily, based on input from prospective users; and (iii) evaluates the prototype Robot Lily on a subject with CLP. The robot has been programmed to interact with the child in a naturalistic manner, using the same language and gestures employed by human speech and language therapists. The robot can respond to inquiries, practice articulation and pronunciation, aid the child with speech fluency, provide feedback, and encourage continued speech exercises. The primary interactions between a child with CLP and Robot Lily were observed and evaluated, with the robot shown to provide a unique opportunity to acquire speech and language abilities in a captivating and interactive manner. Compared to web-based applications, speech education assistant robots like Robot Lily may offer children a more appealing, engaging, and practical solution; and be remotely controlled by humans for specialized interventions at home, thereby circumventing the challenges encountered during COVID-19. These findings and methods have been used to develop an integrated model for ethical robotic speech therapy utilizing machine learning, which is expected to help meet the growing demand for speech therapy services.

Keyword : Human-Robot Interaction (HRI), Speech and Language Therapy, Cleft Lip and Palate, Educational Robot, CNN (Convolutional Neural Network), Language Learning.

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1. Background and Introduction

1.1 Cleft lip and palate (CLP)

Cleft lip and palate (CLP) is a birth defect that affects the formation of the upper lip and palate, preventing the structures from closing. Orofacial clefts of the lip and/or palate are amongst the most common developmental defects, affecting up to 1 in every 700 children (Yilmaz et al., 2019). Children born with cleft lip and palate require extensive specialist care throughout childhood and adolescence, and affects about 10 million people adults worldwide (Sandy et al., 2020). Approximately 30% of children born with CLP will have associated syndromes, with an increased risk of glue ear and auditory processing disorders, which may lead to speech, language, and academic difficulties later in life (van Eeden & Stringer, 2020).

Cleft closure surgery can be performed to correct the anatomical malformations of the lip and palate; however, problems often remain that require follow-on therapy. Difficulties with speech production can result from an inability to articulate certain sounds during the early stages of speech learning; particularly, children with CLP struggle with sounds that require the closure of space between the nose, mouth, and soft palate, including bilabial sounds like /m/ and alveolar sounds like /n/, as well as sounds that require closure between the nasal and oral cavities like those ending /-ɪŋ/. These defects can affect a child’s intelligibility, and ultimately their social and emotional development (Maier et al., 2019).

Speech impairments are one of the most important developmental consequences of CLP (Arai et al., 2021). Speech and language assessments need to be performed after surgery (Arai et al., 2021 and Cleland et al., 2022), and children with isolated CLP require speech and language therapy and additional support (Jurado et al., 2021), which is often not easily accessible, particular in developing countries (Prathanee et al., 2020). There is a need to address the lack of support and barriers to accessing speech services for patients with CLP to ensure they are not developmentally delayed or disadvantaged later in life (Baigorri et al., 2021). By increasing access to speech services and language resources using technology, CLP patients can overcome these barriers.

1.2 The role of technology in speech and language therapy

Regular speech and language therapy is important for children with CLP to ensure that disruptions to normal development are minimised. During the COVID-19 pandemic, where many in-person support services were closed or limited, technology played a vital role in maintaining speech therapy provisions, such as through telehealth (Lyons et al., 2021). Independent of the COVID-19 pandemic, there has been a growing body of research exploring technologies that can augment or assist in speech and language therapy, such as web-based programs that can perform automatic evaluation of speech pathologies (Maier et al., 2019). Some of the benefits of web-based applications include avoiding the need for the end user to install software, access from different platforms—such as mobile devices—and the ability of speech and language therapists to track and monitor progress remotely. Unlike standalone software, web-based interactive applications have the potential to link-up to form part of a cohesive therapy plan, allowing, for example, multiple speech therapists to work collaboratively with a patient, and communicate remotely, improving the patient's experience and likelihood of adherence to therapy. Portable formfactor devices like iPads can be useful for children, with the large screen allowing them to be taught facial and tongue movements, and enable communication with their speech therapist through video conferencing (Dhaky et al., 2021).

1.3 Robot-assisted education and speech therapy

In addition to the development of web-based technologies to aid speech and language therapy, emerging research into AI and robotics has also begun to open up new application areas. Robotics and AI have already been widely explored in education and therapy settings, for example, in speech therapy (Qi et al., 2023; Zhanatkyzy et al., 2019), and in education and assistive technologies for older persons (Chew et al., 2021; Su et al., 2022; Garcia-Sanjuan et al., 2017). Over the past decade, applications of robots for children have also been explored to improve the educational experience of those with disabilities (Ioannou and Andreva, 2019), as classroom aids (Kradolfer et al., 2014), and in language education for children with dyslexia (Mcvey et al., 2022).

Whereas screen-based software for education is limited in its interactive capabilities, as a result of its disembodied nature, robots can physically interact with a child to provide tangible social engagement as an extra feature, which can be considered an advancement over pure software-based learning (Mubin et al., 2013). Studies have shown that robot interaction can help to increase some aspects of social learning, for example, in language production (Warren et al., 2015), with children being more engaged and responsive to educational robots compared to humans or computer screens (Mavadati et al., 2016; Ioannou and Andreva, 2019; Pinto et al., 2015). As a side-benefit, the direct interaction with robotic technology can provide additional motivation for children to engage with learning technology, science, and mathematics. The main advantage, however, of educational robots is in the targeted social interactions, that can increase the child's knowledge in a fun way (Jost et al., 2014). Although the use of a complex new technology, like robots, for teaching skills to young children sounds contradictory, the social and naturalistic manner of Human-Robot Interaction (HRI) means that children can find using robots easier, less complex, and more engaging, as it draws directly on their existing social skills without requiring them to learn a particular interface. Unlike humans, robots also have an advantage in ensuring consistency in their interactions, particularly where repetition of exercises is required. If any variation is required, it can be applied with a minimum effort and in a controlled manner (Huijnen et al., 2017).

A preliminary study describing a speech therapy robot for children with CLP proposed that this approach could be used to gamify the learning experience, help with pronunciation and articulation exercises in a more engaging manner, and increase the availability of therapies to those who cannot access specialised speech and language services (Ramamurthy and Li, 2018; Veleta, 2018).

Studies have shown that the gamification of education activities using robots can support learning (Ioannou & Andreva, 2019). Indeed, gamification has the potential to enhance student motivation and increase engagement (Zourmpakis et al., 2022, 2023; Papadakis et al., 2022, 2023), particularly when combined with social robots (Yang et al., 2023; Tran et al., 2023; Issa et al., 2023). Robots provided many enticements to children, which urge them to continue therapy (Alwadain, Al-Ma'aitah, & Saad, 2020; Spaulding et al., 2018), and interaction with robots has been shown to help children with Autism Spectrum Disorder (ASD) and Delayed Speech Development (DSD) improve their social and communication skills (Bouhali et al., 2023; Amirova et al., 2023; Esfandbod et al., 2023); furthermore, in studies carried out by Warren et al. (2015), children with speech disorders responded better to humanoid robots than adult administrators or typically developing counterparts.

It is worth noting that robots can be automated to aid in therapy for speech-related disorders; however, little research has been conducted on speech therapy robots specifically for CLP. Speech therapy assistant robots are still at an early stage of development, and this research is expected to help fill the growing demand for speech therapy services for children with CLP at home, with various techniques used to motivate children to participate, including playing games, singing songs, and reading books.

1.4 Research overview

Building on the use of emerging technologies for specialist language education and speech therapy, this research project seeks to develop a robot, named Robot Lily, that can support speech therapy specifically for children with CLP, informed by patients and parents, and expert communities of practice. As a first step, the project looks to develop a robot that can support reading and pronunciation learning exercises with children, as reading can be helpful for normal speech development and in building communication skills (McLaughlin, 2011), including auditory comprehension, expressive vocabulary, word memory, and building world knowledge.

In this paper, we describe the initial work to: (i) investigate the user and HRI requirements, usability considerations, and attitudes to speech therapy robots, from the perspective of the parents or carers of children with CLP; (ii) develop an experimental prototype of Robot Lily for CLP language education and speech therapy using a humanoid robot, based on input from prospective users; and (iii) evaluate the prototype Robot Lily on a subject with CLP. These are described in the following sections.

2. Methods

2.1 Survey and requirements gathering

To investigate the needs of parents and carers of children with CLP with respect to language education and speech therapy, a mixed methods survey was designed. The survey consisted of 15 close-ended qualitative and quantitative questions, using multiple choice Likert-type scales, to assess therapy age requirements, as well as experience and attitudes towards robots and educational technologies. In addition, one open-ended question was included to allow free-text responses. The questions were developed into a web-hosted survey, and prefaced with a consent form, using the Qualtrics XM software (Qualtrics, UT, USA). Qualitative responses and survey text were analysed using the thematic analysis method. The utilization of a thematic analysis was employed by the researcher due to the indication provided by the questionnaire themes, which elucidated the beliefs and desires of parents regarding the integration of robots within their domestic environment. Participants were recruited through support networks for parents and carers of children with CLP, including public groups on Facebook and Twitter. The questionnaire was available for two weeks.

2.2 Robot Lily

2.2.1 Software and hardware

The software for the Robot Lily speech therapy assistant was designed based on the requirements gathered from the user survey, and programmed to run on the NAO humanoid robot platform developed by SoftBank Robotics (SoftBank Robotics, 2021). Initial interactions were prototyped using the Choregraphe software, where the robot was programmed to, *firstly*, introduce themselves and interact with the child to learn their face and name to establish a social relationship for subsequent learning, and *secondly*, to lead the child in reading and pronunciation games using a set of cards that contain images and text.

2.2.2 Object recognition and Neural Network

To allow real-time visual object recognition for reading, a Convolutional Neural Network (CNN) was trained for image classification using the image and text cards, and expanded using the CIFAR-10 image dataset of 60,000 colour images (Krizhevsky, Nair & Hinton, 2009), with a 5:1 training to test image ratio. Several network models were constructed using the TensorFlow framework in Python via the Keras API (Abadi et al., 2015; Chollet et al., 2015), and evaluated to select the model with the best classification performance. For the prototype, this CNN was trained and run on a separate PC, with the intention to integrate and deploy the CNN and learning on the

NAO robot using the python-SDK and NAOqi API in following design iterations (SoftBank Robotics, 2021). Details of the system design and CNN models are described in the results section below.

2.3 Ethics and evaluation

The protocol for the survey and evaluations were reviewed and approved by the appropriate Institutional Research Ethics Committee (REC) at Cardiff Metropolitan University. Informed consent was obtained from all survey participants, and survey data was collected and handled in accordance with GDPR and Institutional Policies. Initial usability evaluations were conducted on a single six-year-old female child with CLP in her home environment, under the supervision of the parent-researcher at all times. The researcher observations, with feedback from the researcher's child, were used to inform the design of the system. Both the child and parent had complete autonomy to terminate the interaction with the robot at any point.

3. Results

3.1 Survey results

The survey of parents of children with CLP concluded with a total of 39 responses, with 35 respondents providing complete answers to all of the survey questions. In response to the question of what age they thought would be best to start speech therapy in children with CLP (Figure 1), the majority answered four years old (79.5%), with all remaining respondents answering three years old or younger (20.5%), indicating a strong preference for early intervention, and thus a need for therapy-aids and technologies to be accessible to children in these young age ranges.

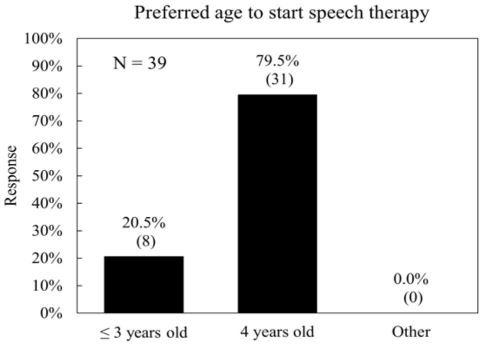

Figure 1: Age – Responses to the question "What do you think is the best age to start speech therapy?"

When questioned about their prior exposure to robots (Figure 2), the overwhelming majority of respondents had not had any previous experience using or working with robots (79.5%). Despite this unfamiliarity with the technology, on average the parents of children with CLP reported a willingness to use the speech therapy assistant robot for their child's speech therapy (Figure 3), with over 61% expressing positive sentiment (47.5% somewhat agreeing, and 19.4% strongly agreeing). Surprisingly, sentiment was even higher when asked about how optimistic they were that a robot could work effectively as a speech therapy assistant (Figure 4), with 65.7% replying positively.

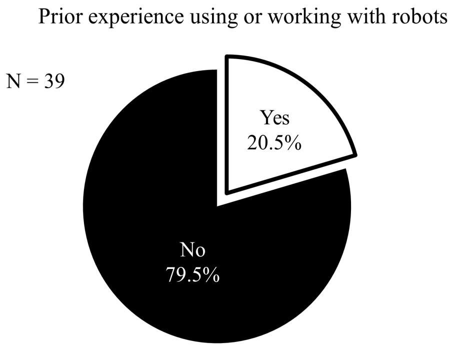

Figure 2: Experience – Responses to the question "Have you ever used or worked with a robot before?"

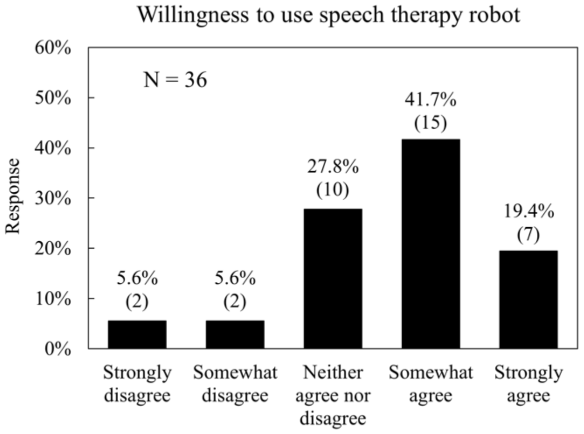

Figure 3: Willingness – Responses to questions relating to the parents' willingness to use a speech therapy robot with their child.

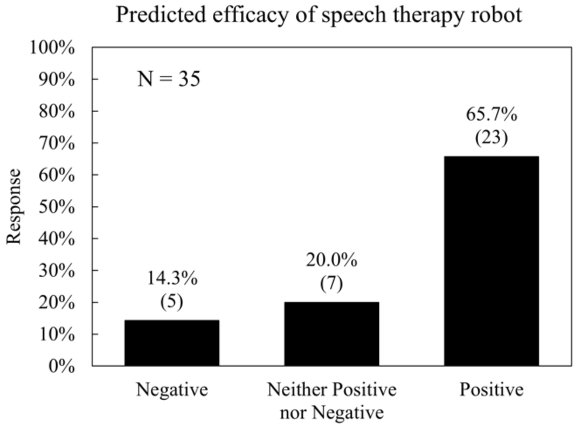

Figure 4: Efficacy – Responses to "How optimistic you are that robots can work as speech therapy assistants?". Positive and negative responses were consolidated into the respective categories.

In the free-text responses, some parents expressed concerns about the accent that a robot might use, while others doubted the suitability of a robot for language education and speech therapy. One parent said *"I don't think a robot can provide the language therapy. For speech therapy alone, a robot wouldn't be any different to an app or an iPad"*; highlighting a need to clarify the strengths and weaknesses of robots as learning tools in comparison to screen-based apps, and to communicate these clearly to the intended users—particularly around the social learning, engagement, and motivation aspects of educational robots. Some parents also raised concerns about how lip and tongue movement would be communicated with a robot that does not have a human-like mouth.

3.2 Implementation – Robot Lily prototype

Based on the requirements from the CLP survey, along with informal feedback on how children may prefer to interact with the robot, an initial prototype of Robot Lily was created (Figure 5), with interactions taking place in two stages: (i) In the first meeting Robot Lily introduces itself, and interacts with the child to learn their name, which it can associate with the facial image of the child to recognise and greet them later; (ii) in the second meeting, and in all the later meetings, Lily uses the data it has stored to greet the child, and through a series of dialogues gives them the options to play games, where they can practice their reading and pronunciation using text and image cards, or to read a book together.

In the reading exercise games, the child can present Robot Lily with a text and image card, which the robot reads and encourages the child to repeat (Figure 6). If the child pronounces the word correctly, they receive positive feedback from the robot, and are asked for the next card; however, if their pronunciation is incorrect, the child is asked to repeat the word again. If the child does not pronounce the word correctly after three attempts, the mistake is logged via email for review by the parent and/or speech therapist, and the game continues with the next item. Evaluation of speech is based on different performance parameters.

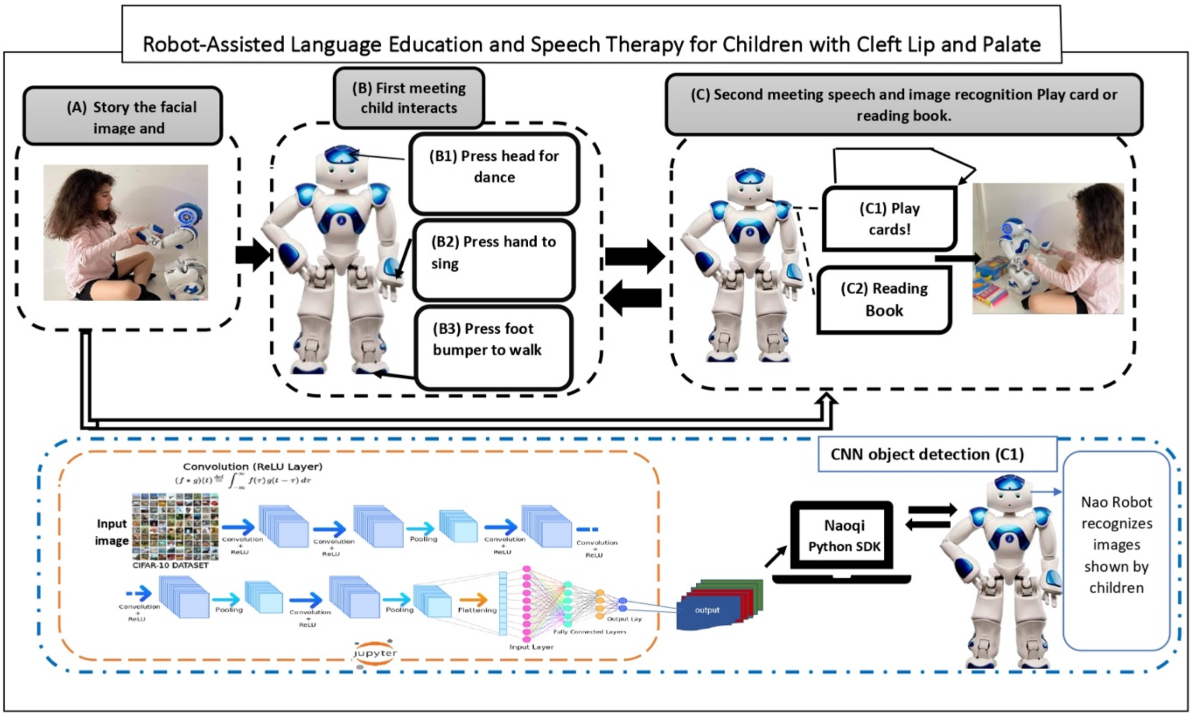

Figure 5: Robot-Assisted Language Education and Speech Therapy for Children with CLP – A diagram showing the Robot Lily system architecture, and example interactions that can be used for language education and speech therapy in children with CLP.

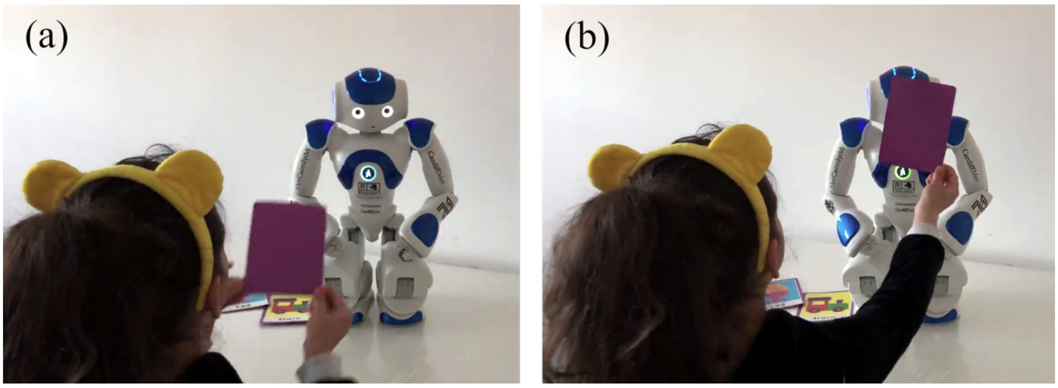

Figure 6: Child-Robot Interaction – Showing the research subject with CLP interacting with the Robot Lily speech therapy assistant. In an example interaction, the child (a) selects a card for the robot to read to, following which (b) the robot asks the subject to read the word on the card and provides feedback on the child's pronunciation.

3.3 CNN model training NAO for image recognition

As mentioned in Section 2 above, to improve the visual image recognition in the Robot Lily prototype, we explored the use of a Convolutional Neural Network (CNN) for image classification. In the initial training, three CNN models were trained on the CIFAR-10 dataset, with the best model (Model 1) yielding 0.92 and 0.78 accuracy in training and validation, respectively (Table 1). Given the consistent ability to accurately predict image classes in the prototype (Figure 7), we selected this model as the basis for future image classification in the Robot Lily speech therapy assistant robot.

Table 1: CNN results – Comparison of three CNN models for image classification.

Model	Training Accuracy	Validation Accuracy	Training Loss	Validation Loss	No. Epochs	Batch Size
1	0.92	0.78	0.26	0.85	1000	150
2	0.73	0.68	0.73	0.91	1000	150
3	0.72	0.70	0.76	0.83	1000	150

The model consisted of a feature map of convolutional layers, pooling and dropout. The convolutional layer in the CNN is used to extract features of image, while the pooling is used to reduce the number of features to reduce computational requirements. Dropout is used to randomly drop neurons to regularize the neural network. A summary of the network structure is shown in Table 2.

Table 2: Model 1 summary – Layers and parameters the Sequential CNN in TensorFlow.

Layer (type)	Output Shape	No. Param
conv2d (Conv2D)	(None, 30, 30, 32)	896
conv2d_1 (Conv2D)	(None, 28, 28, 32)	9248
max_pooling2d (MaxPooling2D)	(None, 14, 14, 32)	0
dropout (Dropout)	(None, 14, 14, 32)	0
conv2d_2 (Conv2D)	(None, 12, 12, 64)	18496
conv2d_3 (Conv2D)	(None, 10, 10, 64)	36928
max_pooling2d_1 (MaxPooling2D)	(None, 5, 5, 64)	0
dropout_1 (Dropout)	(None, 5, 5, 64)	0
conv2d_4 (Conv2D)	(None, 3, 3, 128)	73856
max_pooling2d_2 (MaxPooling2D)	(None, 1, 1, 128)	0
dropout_2 (Dropout)	(None, 1, 1, 128)	0
flatten (Flatten)	(None, 128)	0
dense (Dense)	(None, 256)	33024
dropout_3 (Dropout)	(None, 256)	0
dense_1 (Dense)	(None, 128)	32896
dropout_4 (Dropout)	(None, 128)	0
dense_2 (Dense)	(None, 10)	1290
Total params		206,634
Trainable params		206,634
Non-trainable params		0

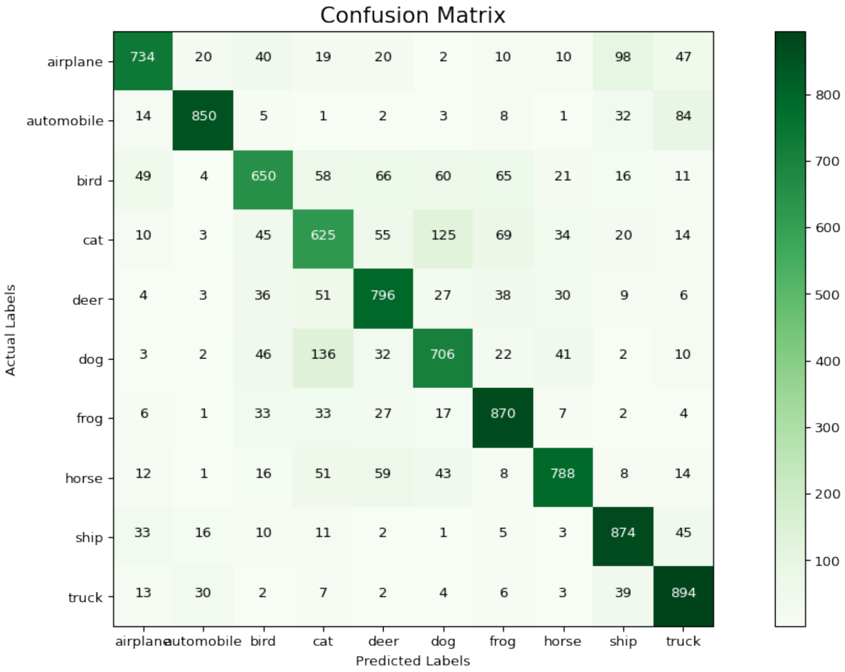

Figure 7: Confusion matrix – Classification performance of the image classification model of Robot Lily on a subset of images, comparing predicted to actual labels. The centre diagonal illustrates correct classification on the majority of images.

3.4 Robot evaluation

The Robot Lily prototype was evaluated with the six-year-old subject with CLP (Figure 6) on three separate occasions. In all cases, we observed that the subject maintained a high level of engagement with the robot throughout the activities, on both the reading and card-based exercises. Robot Lily correctly classified all of the text and image cards used in the exercises, however, in some instances, the fluidity of interaction was interrupted by the long response times of the robot. From an HRI usability perspective, one issue was observed in the robot's occasional failure to understand the subject's requests. In these cases, it was usually the result of the subject requesting interactions that fell outside the scope of Robot Lily's programming. For example, when at the end of the second meeting the robot asked, "do you need anything else?", the child replied, "can I hug you?", to which Robot Lily responded: "Sorry. I cannot understand you".

4. Conclusion and discussion

4.1 Summary

For children with CLP, regular speech therapy is essential to prevent the development of communication difficulties; however, access to speech therapists is not always available, as was witnessed during the COVID-19 pandemic. This paper has described the use of a robot assistant that can augment speech therapy and be remotely controlled by human therapists for specialist interventions at home, while also providing a novel and engaging approach to language education and speech therapy for children. The robot has been programmed to interact with the child in a naturalistic manner, using the same language and gestures used by human speech and language therapists to help the child with speech fluency, provide feedback, and encourage them to keep practicing their speech exercises. We observed and evaluated the primary interactions between a child with CLP and Robot Lily, finding that the robot can provide a unique opportunity to learn speech and language skills in an engaging and interactive way. From conducting the first survey on educational robots amongst parents of children with CLP, we found that the majority view the use of robots for speech therapy positively, and would be willing to use them with their own children.

The nativistic theory is the theoretical framework underpinning this study involving Robot Lilly. This particular theory has demonstrated efficacy in facilitating communication among children experiencing speech difficulties, thereby aiding in the surmounting of such issues. Integrating interactive testing studies with the nativistic theory presents an opportunity to provide optimal support for both children and their caregivers in instances where traditional support systems may be insufficient.

4.2 Future work

Further improvements, adjustments and research is required to improve the capabilities of the robot, and build the trust of parents and speech therapists. As seen from the initial evaluation, the naturalistic and human-like interactions that the robot facilitates can create a sense of engagement that supports the learning process; however, they can also lead to unrealistic expectations from users that the robot should possess human-like capabilities for which it is not designed, such as giving hugs (Section 3.4 above). Additional HRI research is required to determine how best to address these expectation-capability mismatches without compromising the social connection that the user has formed with the robot.

Future plans include expanding the CNN model on CLP children to increase the image recognition capability, and to conduct more extensive evaluations with parents whose children have CLP. Following these enhancements, updated versions of Robot Lily will be evaluated in clinic and hospital settings.

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