A. Technical Details

1. An Artificial Cognitive Agent for a Robust Child-Robot Conversation

We developed a rule-based artificial cognitive agent to allow a robot to autonomously manage a multi-session child-robot conversation. Sensor data, like audio from the microphones and button presses, are streamed to the agent. The agent has access to services, like Google Dialogflow for speech and intent recognition, and a database for persistent storage. The agent has a knowledge base filled with templated minidialogs with meta-data that includes a topic, required information to fill the template gaps, and relationships to other minidialogs. The knowledge base also has a multi-session template specifying required dialogs and goals for each session.

Finally, the agent has a rule base that specifies rules for dialog management and personalization. For example, there are rules in place specifying the recognition and repair pipeline. Children get two speech attempts first and can fall back to entering their answer using a tablet. Using the incoming data, the available knowledge, and rules, the agent can reason about which action to take next. It selects actions on a micro level (e.g. turning on a microphone, speaking, or gesturing) and on a macro level (e.g. which minidialog to select next). More details can be found in [1].

A key factor determining the robustness of the conversation is speech recognition performance. Poor performance lowers conversational comfort and inhibits relationship formation [2]. In the user study the robot used the speech recognition 8901 times. The recognition rate after the first attempt is 77% and after two speech attempts 86%. Meaning only in 14% of the time the tablet was necessary, safeguarding that always an answer could be provided. 95% of the participants indicated they felt the robot could understand them well. These performance metrics confirm that our implementation indeed provides a robust and comfortable child-robot conversation.

2. Math Task

In Table 1. the difficulty levels for a math problems are displayed. In Table 2. the different guidance strategies for the scaffolding condition are displayed.

Table 1. Math problem difficulty levels.

Level	Problem	Example
0	{2, 5, 10} x [2, 10]	5 x 8
1	[2, 10] x [2, 10)	3 x 7
2	[2, 10] x [1, 10) * 10	6 x 60
3	[2, 10] x [1, 10) * {100, 1000}	8 x 700
4	[2, 10] * 10 x [2, 10) * 10	30 x 40
5	[2, 10] x [11, 19]	9 x 13
6	[11, 19] x [2, 10) * {10, 100, 1000}	17 x 6000
7	[2, 10] x [11, 99]	4 x 76
8	[2, 10] x [11, 99] * {10, 100}	5 x 340
9	[11, 99] x [2, 9] * {10, 100, 1000}	45 x 700
10	[11, 19] x [11, 19]	12 x 14
11	[11, 99] x [11, 99]	34 x 65

Table 2. Guidance strategies

Name	Level	Example	Guidance
Table	0, 1 (2x, 5x, 10x)	5 x 4	Let's write down all the members of this multiplication table and solve them one by one until we get to our sum.. 5x1=, 5x2=, 5x3=, etcetera.
Small Sum	2, 3, 6	3 x 400	400 is 100 times bigger than 4. We can first solve 3 x 4. We call this the small sum. Then we can multiply the answer with a 100 to get to 3 x 400.
Support Sum	1 (3x, 6x, 9x)	6x7	Let's find the nearest support sum. Found it! It's 5x7. Our sum is only7 away from the support sum. Let's first solve 5x7 and then add 7 to get our answer.
Double	1 (4x, 8x)	4 x 9	Let's double our way to the answer. We start with 2 x 9. If we double the answer, we get to 4x9.
Split	5, 7	6 x 17	Let's split 17 into 10 and 7. This gives two helper sums we have to solve. 6x10 and 6x7. By adding the answers to both helper sums, we get the answer we are looking for.
Split 7	1 (7x)	7 x 9	We can split 7 up in to 2 and 5. This gives two helper sums we have to solve. 2x9 and 5x9. By adding the answers to both helper sums, we get the answer we are looking for.
None	8, 9, 10, 11		No strategy is provided, just a second change.

B. Creative Details

1. Child-Robot Storyworld

A storyworld is a tool for creating dialogs for a multi-session child-robot conversation [1]. It is a transmedia narrative that situates the robot in a fictional world and connects it to the real world. Our storyworld describes the robot as a story character, with hobbies and quirks, but it takes into account its real physical and cognitive capabilities and limitations. This provides the necessary anchor points and topics for writing short connected dialogs. Hobbies can, for example, include cooking (albeit clumsily), but not swimming (because it would short circuit). A key quirk is the robot's curiosity. It provides a motivation for why the robot asks so many questions. The storyworld furthermore provides fictional goals the robot wants to achieve. For example, the robot is trying to figure out what kind of robot it wants to become. This lead to a series of dialogs about different jobs the robot has tried out. The storyworld also describes goals the robot wants to achieve in the real world. The main goal is, of course, helping the child improve their math skills. Dialogs are created to reflect these goals.

C. Data Details

1. Questionnaire

In Table 3 the individual items for the Likert scales for Social Presence and Feeling of Friendship are provided together with the manipulation checks. In Table 4 and 5 the mean scores for the Social Presence and Feeling of Friendship individual items are provided.

Table 3. Items of Social Presence, Feelings of Friendship, Manipulation Checks.

	Items	*M*	*(SD)*
Social Presence[1]	SP1. Did it feel like you were calculating with a real person?	3.06	(.745)
	SP2. Do you think the robot can see you?	2.94	(.869)
	SP3. Do you think the robot understands you?	3.39	(.550)
	SP4. Do you think the robot can have feelings (e.g. sadness or joy)?	2.72	(.874)
	SP5. Do you think the robot is a living creature?	2.11	(.883)
Feelings of Friendship[1]	F1. Do you feel comfortable around the robot?	3.77	(.491)
	F2. Does the robot suit you well?	3.40	(.642)
	F3. Does the robot feel like a friend to you?	3.54	(.612)
	F4. Would you like to chat further with the robot?	3.82	(.445)
	F5. Would you like to do more activities with the robot?	3.84	(.409)
	F6. Would you like to see the robot more often?	3.88	(.344)
Manipulation Checks	MC1. Did you find the math stories the robot told interesting?[1]	3.36	(.622)
	MC2. Did the robot use things you said while chatting to create a math story?[1]	3.35	(.857)
	MC3. Did the robot help you if you didn't know the answer or got the sum wrong?[1]	3.14	(1.023)
	MC4. Did you feel that the robot matched the math level to you?[1]	3.20	(.802)
	MC5. How did you find the calculations?[2]	2.48	(.818)

[1]Answer scales: 1 = *no, definitely not* till 4 = *yes, definitely so*; [2]Answer scales: 1 = *Way too easy* till 5 = *Way too difficult.*

Table 4. Mean scores on Social Presence by study condition.

	Items	Personalization	Guidance	*M*	*(SD)*
Social Presence	SP1. Did it feel like you were calculating with a real person?	No	No	2.97	(.129)
			Yes	3.26	(.127)
		Yes	No	3.12	(.134)
			Yes	2.97	(.127)
	SP2. Do you think the robot can see you?	No	No	2.79	(.147)
			Yes	3.00	(.145)
		Yes	No	2.94	(.152)
			Yes	3.08	(.144)
	SP3. Do you think the robot understands you?	No	No	3.22	(.094)
			Yes	3.44	(.093)
		Yes	No	3.49	(.097)
			Yes	3.45	(.093)
	SP4. Do you think the robot can have feelings (e.g. sadness or joy)?	No	No^{b}	2.41	(.149)
			Yes^{a}	2.87	(.146)
		Yes	No^{ab}	2.78	(.154)
			Yes^{ab}	2.75	(.146)
	SP5. Do you think the robot is a living creature?	No	No^{b}	1.97	(.149)
			Yes^{a}	2.27	(.147)
		Yes	No^{b}	1.98	(.154)
			Yes^{a}	2.27	(.147)

Note: Reported means and standard deviations are corrected for covariates gender and math level.
^{a,b} Row differences significant at $p < .05$.

Table 5. Mean scores on Feelings of Friendship by study condition.

	Items	Personalization	Guidance	*M*	*(SD)*
Feelings of Friendship	F1. Do you feel comfortable around the robot?	No	No	3.81	(.075)
			Yes	3.77	(.074)
		Yes	No	3.79	(.077)
			Yes	3.82	(.073)
	F2. Does the robot suit you well?	No	No	3.38	(.102)
			Yes	3.39	(.100)
		Yes	No	3.55	(.105)
			Yes	3.42	(.100)
	F3. Does the robot feel like a friend to you?	No^{b}	No	3.47	(.096)
			Yes	3.48	(.094)
		Yes^{a}	No	3.72	(.099)
			Yes	3.57	(.094)
	F4. Would you like to chat further with the robot?	No	No	3.87	(.071)
			Yes	3.80	(.070)
		Yes	No	3.83	(.074)
			Yes	3.82	(.070)
	F5. Would you like to do more activities with the robot?	No	No	3.88	(.071)
			Yes	3.73	(.070)
		Yes	No	3.93	(.073)
			Yes	3.85	(.070)
	F6. Would you like to see the robot more often?	No	No	3.88	(.053)
			Yes	3.91	(.053)
		Yes	No	4.00	(.055)
			Yes	3.82	(.053)

Note: Reported means and standard deviations are corrected for covariates gender and math level.
^{a,b} Row differences significant at $p < .05$.

D. Ethical Details

We followed a child-centered design approach, this includes, for example, configuring the software and the study set-up in such a way we can safeguard the privacy of children. The speech recognition and memory system did not process identifiable information (e.g. child's name). The child's name was entered manually in the system each session, for using it during the conversation, and was not persistently stored. The child's preferences that were stored, were selected based on their low-risk nature (e.g. favorite farm animal, (dis)like of reading). See chapter 6.6 in [1] for a more extensive discussion of the ethical considerations that are important to make for these type of applications and running these type of studies.

References

[1] M. E. U. Ligthart, "Shaping the Child-Robot Relationship: Interaction Design Patterns for a Sustainable Interaction," PhD-Thesis - Research and graduation internal, Global Academic Press, Culemborg, 2022.

[2] M. E. U. Ligthart, M. A. Neerincx, and K. V. Hindriks, "Getting acquainted: First steps for child-robot relationship formation," *Front. Robot. AI*, vol. 9, 2022, Accessed: Sep. 19, 2022. [Online]. Available: https://www.frontiersin.org/articles/10.3389/frobt.2022.853665