Automating Cancer Genetic Counseling with an Adaptive Pedagogical Agent

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Effective communication of genetic risk is increasingly important for prevention and treatment of hereditary cancer syndromes. Many individuals do not have access to genetic counselors, or lack the ability to understand and act on genetic risks, due to the complexity of the information. Automated approaches that incorporate animated pedagogical conversational agents may address these barriers. We describe a pedagogical agent that functions in the role of a virtual genetic counselor that discusses hereditary breast cancer risk and motivates women to obtain breast cancer screening. We report the design and evaluation of two prototypes of the virtual counselor. Our results demonstrate the feasibility of this approach, and the effectiveness in improving breast cancer genetics knowledge, by adapting the virtual counselor's pedagogical strategies to an individual's comprehension based on dynamic assessments and preferences.

CCS CONCEPTS • Human-centered computing → Human computer interaction (HCI) → HCI design and evaluation methods • Computing methodologies → Intelligent agents

Additional Keywords and Phrases: Embodied conversational agent, Pedagogical agent, Intelligent tutoring system, Genetic counseling, Genetic risk communication, Health education

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1 INTRODUCTION

Genetic risks estimate how genes affect an individual's likelihood of developing certain diseases, such as hereditary cancer syndromes. Advancements in genomic research call for greater efforts to increase the awareness of genetic risks and their implications for an individual's health [1]. Medical guidelines on genetic risks recommend risk-reducing behaviors and preventive measures, such as genetic screening, cancer screening, lifestyle behavior change, medications, or preventive surgeries. Effective communication of genetic risks is vital in helping at-risk individuals make appropriate health related decisions and adhere to risk-reducing guidelines [2]. Adherence to recommended guidelines has been found to be increasingly important for cancer prevention and treatment. For example, an increase in breast cancer screening rates in recent years contributed to the decrease in breast cancer mortality rates, which dropped from 33.1% in 1990, to 20.1% in 2015, due to a combination of early detection screening and advancement in treatments [3]. However, awareness of genetic risk is still low in the general population, despite high levels of interest [1], and more work is needed to improve at-risk individuals' adherence to the recommended medical guidelines [4]. While human genetic counselors are effective at communicating risk and motivating adherence, a majority of at-risk individuals do not have access to these experts, due to various logistical barriers, exacerbated by a national shortage of genetic counselors in the United States [5].

In addition to lack of access, difficulties understanding genetic risks represent another barrier to adherence, given the complexity of the information. Communication of genetic risk often involves discussing complex genetic concepts, and a large amount of numerical or statistical information, including relative risk, absolute risk, probabilities, and frequencies [1, 6-8]. Communicating numerical or statistical risk information remains a difficult task, especially for individuals who have difficulty understanding health or numeric concepts [1, 7-10]. In the United States, more than one-third of adults have limited health literacy [11], the ability to read, understand, and act on health information [12]; and more than half have limited health numeracy [13], the ability to access, understand, communicate, and act on numerical, graphical, biostatistical, and probabilistic health information [9]. Individuals with limited health literacy and numeracy have poorer health outcomes and they are less likely to obtain health information from written resources such as educational brochures and the Internet [7, 8, 10, 11, 14]. In particular, individuals with limited health numeracy, compared with their more numerate counterparts, often have more difficulty interpreting complex graphs, assessing risks, and making informed decisions using numerical risk information [9, 10].

To provide more easily accessible genetic counseling and to improve the communication of genetic risk for low literacy and numeracy users, we have developed a pedagogical agent that functions in the role of a virtual genetic counselor. The virtual counselor is implemented as an embodied conversational agent (ECA), which is an animated humanoid computer character that simulates face-to-face counseling conversations. Our approach integrates techniques from the intelligent tutoring systems (ITS), including dynamic adaptation to user comprehension maintained in a student model, with counseling techniques for risk communication. Our initial test domain is genetic counseling for hereditary breast cancer, which is one of the most common hereditary cancer syndromes.

In the rest of this paper we first review related work and risk communication strategies, before describing the design of our virtual genetic counselor. We then describe the evaluation of two prototypes before closing.

2 RELATED WORK

2.1 Embodied Conversational Agents as Health Counselors

Embodied conversational agents use non-verbal behaviors such as gaze and hand gestures that accompany speech, to express empathy and other emotions [15]. Previous research has demonstrated that ECAs can work effectively as health educators and health counselors in several areas of health behavior change, and they are particularly effective in helping individuals with limited health literacy [16-18]. Bickmore and colleagues have conducted a series of studies looking at how pedagogical ECAs can help explain complex medical documents to individuals with low health literacy, and in general found participants' experience and satisfaction of the process improved [18-20]. Wang et al. [21] developed an ECA genetic counselor, which was able to work with patients to document their family history. This system was shown to be highly effective for users with low health literacy; however, it was not designed to educate patients about their genetic risk.

2.2 Intelligent Tutoring Systems

Intelligent tutoring systems are computer tutors able to provide tailored education, while maintaining a dynamic model of an individual's current knowledge state. Traditionally, ITSs have been mostly applied in the context of science-related classroom learning, such as mathematics, physics, or entry-level programming [22, 23]. Intelligent tutoring system theories and techniques are particularly relevant to genetic risk communication, as a typical genetic counseling session often resembles a one-on-one tutoring session, involving a significant amount of educational content. During the dialogue, genetic counselors are often able to gauge their client's risk perception, receive immediate feedback, and then make appropriate adjustments on the risk information they want to deliver [2].

There has been extensive research applying ECAs in the field of ITS ("pedagogical agents"). Graesser and colleagues developed the AutoTutor system [24-26], which is an animated conversational agent that simulates the discourse patterns and pedagogical strategies of a human tutor. One version of the AutoTutor system, the Affective AutoTutor, is able to automatically detect and adapt to a student's emotional states as well as his/her cognitive states [27]. Evaluation studies showed that Affective AutoTutor resulted in significant improvements in learning compared with the original AutoTutor, particularly for students with lower levels of knowledge.

Wolfe et al. reported an ITS system called BRCA Gist [28, 29], which is an intelligent tutor similar to AutoTutor. BRCA Gist is able to teach women general concepts about genetic testing and breast cancer risk, using natural-language dialogues. However, learning with BRCA Gist resembles more of a classroom experience rather than a counseling session, and it does not provide information a patient would typically receive from a genetic counselor, such as specific risk rates or tailored recommendations for risk-reducing behaviors.

3 RISK COMMUNICATION

Over the past decades, researchers in health and risk communication have conducted extensive research regarding how risk information should be presented to individuals in order to improve comprehension, promote informed decision-making, and encourage health behavior change. This body of research covers areas such as presentation formats of numerical risk information, framing effects, and use of graphics. Table 1 shows eight of the principles from this literature related to communication of risk to individuals with low health literacy and numeracy that we have incorporated into the design of our virtual genetic counselor.

Table 1: Selected Genetic Risk Communication Principles

	Principles	Explanations	References
1	Communicate using plain language.		[30]
2	Providing only key information is more effective.	The presentation format should always make the most important information easier to perceive and evaluate, requiring less cognitive efforts.	[8, 10, 30, 31]
3	Tailor communication to patient profiles.	Risk information should be tailored to an individual's specific genetic profiles and other characteristics.	[31]
4	Pay attention to framing effects.	Present both positive and negative outcomes, or gain- and loss-framed numerical risk information (e.g., survival and mortality rates) to reduce framing effects.	[2, 7, 8, 10, 31, 32]
5	Always present absolute risks.	There is mixed evidence regarding whether relative risks should be presented along with absolute risks. But existing guidelines agree that absolute risks should always be presented.	[10, 30, 33, 34]
6	Use multiple formats to present statistical risk information.	Existing guidelines suggest that the format of frequencies is preferable to the format of percentages.	[7, 30, 31, 34]

	Principles	Explanations	References
7	Use verbal expressions along with numerical information.	Use verbal expressions, such as “common”, “rare”, “seldom”, “sometimes”, “more often than not”, together with numerical probabilities, to contextualize the risks.	[8, 34]
8	Use different graphs based on the numerical information presented.	1) Pictographs or frequency diagrams can be used to present risk and benefit information. The random highlighting of a frequency diagram can be used when explaining the concept of chance. 2) Bar graphs are particularly effective in making multiple comparisons and depicting relative risks. 3) Histograms and pie charts can be used to emphasize part-to-whole concepts such as percentages. 4) Line graphs effectively communicate trends. 5) Scatter plots effectively display variability.	[7, 8, 10, 30, 31, 34-37]

4 VIRTUAL COUNSELOR SYSTEM DESIGN

The virtual genetic counselor is developed and rendered in the Unity3D game engine (Figure 1). The counselor’s dialogues are scripted using a custom scripting language. The counselor speaks using synthetic speech synchronized with nonverbal behavior generated using BEAT [38], including facial displays of emotions, gaze shifts, eyebrow raises, head nods, body posture shifts, and hand gestures. Users converse with the counselor by selecting utterance options from a multiple-choice menu shown on the screen, updated at each turn of the conversation.

Figure 1: The virtual genetic counselor discusses breast cancer risk with users

4.1 Prototype I Design

We developed an initial Prototype I (PI) to evaluate feasibility of the proposed virtual counselor. PI educates users about their breast cancer genetic risk, and also motivates them to adhere to recommended breast cancer screening guidelines. The virtual counselor starts with a short social chat conversation, designed to establish trust and rapport with its users, followed by different educational modules that cover topics typically discussed during a genetic counseling session. At the end of each module, the virtual counselor asks users short quiz questions in order to assess their comprehension. The design of PI’s pedagogical strategies is guided by the principles for genetic risk communication discussed previously. The educational modules are as follows:

- *Hereditary Breast Cancer:* This module talks about the definition of hereditary breast and ovarian cancer, its prevalence in the general population, and how one might be at risk for this familial cancer syndrome.
- *Genes and Mutations:* This module covers the basic facts about genes, chromosomes, and genetic mutations. Specifically, the virtual counselor explains what BRCA mutations are, and the relationship between BRCA mutations and hereditary breast and ovarian cancer.
- *Personalized BRCA1 and BRCA2 Genetic Risks:* Tailored risk rates are given based on the user's age and gender. The virtual counselor explains the user's specific risks for breast and ovarian cancer, respectively, with or without a BRCA1 or BRCA2 mutation. The virtual counselor also discusses other risk factors, such as ethnicity and family medical history, and how these risk factors might affect an individual's risk.
- *Recommended Guidelines:* This module discusses the recommended guidelines for breast cancer prevention and detection, and explains the different screening methods and other risk-reducing options.
- *Genetic Testing:* This module educates the user about genetic testing, particularly BRCA genetic testing, and the possible results someone may receive from a genetic test.
- *Adherence Motivation:* The virtual counselor motivates users to follow the recommended medical guidelines, and also suggests BRCA genetic testing, if the user is deemed at risk for hereditary breast cancer.

4.2 Prototype II Design

We extended our initial prototype to assess the efficacy of ITS-inspired dynamic adaptation in risk education. Prototype II (PII) adopts a standard ITS architecture, consisting of four main components [23]: a domain knowledge model which contains the entire educational content; a student model which maintains a dynamic model of the user's comprehension through periodic quiz assessments, as well as other user variables; a pedagogical module that dynamically chooses its teaching strategies and explanation methods, based on the student model's current assessment and the discourse context; and an ECA interface that handles the interaction between the user and the virtual counselor. In addition to the risk communication principles discussed earlier, the design of PII is also guided by successful intelligent tutoring tactics, including setting goals, providing short immediate feedback, and explaining errors [39-41].

In PI, all users receive the same educational content, despite comprehension assessment in each module. In PII, the pedagogical content a user receives are tailored based on dynamic assessments and other user traits maintained in the student model, including the following:

- *User preferences:* Users receive pedagogical content adapted to their preferences indicated during dialogue: narrative versus visual explanations; whether they would like to receive alternative risk explanations when applicable.
- *Health literacy and numeracy assessed at baseline:* Users with limited health literacy first see or hear graphics and risk explanations designed to best help individuals with limited health literacy or numeracy, according to risk communication theories. They are able to receive additional help based their preferences.
- *Prior knowledge screening:* During the conversation, the virtual counselor assesses users' prior knowledge in this domain using a series of true or false questions, e.g., knowledge regarding hereditary cancer, genes, etc. Users with adequate prior knowledge receive adapted educational content, though given options to review any skipped content.
- *Dynamic comprehension assessments:* Users receive tailored pedagogical content based on assessments of their knowledge state (periodic quizzes), e.g., alternative risk explanations, review of previous topics, etc.

5 EVALUATION STUDIES

5.1 Study Design and Measures to Evaluate Prototype I and Prototype II

We conducted two quasi-experimental studies to evaluate the two prototypes. Study I was designed to evaluate the acceptability and feasibility of PI. At baseline, participants' heath literacy was assessed using the Newest Vital Sign instrument [42], and health numeracy was assessed using a validated instrument from [43]. All participants interacted with the virtual counselor (Tanya) in a single 30-minute session on a desktop computer. A breast cancer genetics knowledge scale (range 1-11), modified based on an instrument validated in past research [44-46], was administered both immediately before and after the interaction. Self-report single-item scales were administered after the interaction (Table 2).

Study II was designed to evaluate the effectiveness of the adaptive risk education, implemented in PII. Study II used the same design as Study I. In addition to measurements collected in Study I, participants were asked to rate the level of adaptation and tailoring they received (7-point single item, Table 2). A semi-structured interview was conducted at the end of the counseling session, focusing on participants' perceptions of the virtual counselor's dynamic assessments and pedagogical strategies. Both studies were approved by our university IRB. Participants were recruited from a university campus and through online advertising, and were compensated for their time.

Table 2: Acceptance of and satisfaction with the virtual counselor. Single-item scales. Anchors: 1="not at all" to 7="very much" except where noted. One-sample Wilcoxon signed rank tests demonstrating ratings significantly different from neutral (=4).

Single-Item Scales	Study I Median (IQR)	Study I p-value	Study II Median (IQR)	Study II p-value
How satisfied were you with Tanya?	6 (0.25)	<.01*	6 (2)	<.01*
How satisfied were you with the entire experience?	6 (0.5)	<.01*	7 (2)	<.01*
How much did you like Tanya?	5.5 (1)	<.01*	6 (2)	.03*
How much did you trust Tanya?	6 (1.25)	<.01*	6 (1)	<.01*
How knowledgeable was Tanya?	6 (1)	<.01*	7 (1)	<.01*
How accommodating/tailored do you feel Tanya was to your preference?	N/A	N/A	7 (1)	<.01*
How much information did you get? (1=too little; 4=just right; 7=too much)	4 (1.25)	n.s.	4 (1)	n.s.
How likely would you make a commitment to follow the recommended guidelines for breast cancer screening?	6 (2)	<.01*	6 (1)	<.01*
How likely would you be willing to talk more about your breast cancer risks with your primary care doctor or a genetic counselor?	7 (1)	<.01*	5 (2)	<.01*

5.2 Study I Results – Prototype I Evaluation

Twelve English-speaking females participated in Study I. Participants (N=12) aged 21-63 years old (median=23.5), 41.7% white, 25% Hispanic, 16.7% black, 16.7% Asian. Two participants (16.7%) had limited health literacy.

Participants' post-treatment scores for the breast cancer genetics knowledge scale (mean=9.8, SD=0.9) significantly increased compared with their pre-treatment scores (mean=4.9, SD=2.2), paired $t(11)=-7.01$, $p<.001$ (Figure 2). One-sample Wilcoxon signed rank tests were conducted for single-item scale outcomes, to determine if sample medians were significantly different than neutral (Table 2). Overall, participants were satisfied with the virtual counselor and the counseling experience. They liked the virtual counselor, trusted her, and found her very knowledgeable. When asked about their perceived amount of information received, participants rated neither too much nor too little (one-sample Wilcoxon, p<.01). Participants were willing to follow the recommended medical guidelines, and were also willing to talk more about genetic risk with a healthcare professional.

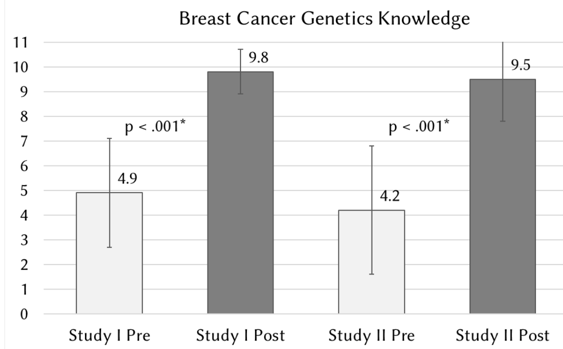

Figure 2: Participants' post-treatment knowledge scores significant increased compared with pre-treatment scores, in both Study I and Study II, paired t-tests. Mean scores shown, error bars depicting standard deviations.

5.3 Study II Results – Prototype II Evaluation

Thirteen English-speaking females participated in Study II. Participants (N=13) aged 19-30 years old (median=22), 46.1% white, 38.5% Asian, and 15.4% black. Two participants (15.4%) had limited health literacy. Using median score as a cut off score (median=10, range 1-11), five participants (38.5%) were categorized as having limited health numeracy, answering more than one questions incorrectly. All participants had at least some college education.

Participants' post-treatment knowledge scores (mean=9.5, SD=1.7) significantly increased compared with pre-treatment scores (mean=4.2, SD=2.6), paired t(12)=-5.79, p<.001 (Figure 2). Single-item scale outcomes were listed in Table 2. In Particular, participants found the virtual counselor very knowledgeable (median=7), and very accommodating or tailored to their preferences (median=7).

5.4 Study II Qualitative Analysis

We audio-recorded and transcribed the semi-structured interviews conducted in Study II (in total 165 minutes of audio files, 122 pages of transcription). The interview transcriptions were analyzed following a general inductive approach adopted from [47]: the transcripts were read repeatedly to obtain a general understanding of the content; initial concepts were coded, reviewed, and clustered, to form higher-level themes. The analysis was conducted using the NVivo 12 software. During the interview, participants mainly answered questions regarding their perceptions of the virtual counselor's pedagogical strategies. Selective themes were reported here:

Graphics improve understanding and recall of genetic risk information: The graphics and visual aids used by the virtual counselor helped conceptualize the risk messages delivered, and also made it easy for participants to recall. P4 described how a pictograph helped explain the risk, *"The one I remember the most was she was just explaining the statistics…I think it was like 12 in 100 women will get breast cancer and…she showed like 100 little figurines, and like 12 of 'em were colored in, to represent how many people would get cancer, so I like that it was really easy to see and you know, conceptualize (with the graphics)."* Several participants found the pictographs useful, e.g., *"I'm definitely a visual learner, so I thought it was helpful to be able to actually visualize the risk in terms of like...this many people out of a certain number, or the lifetime likelihood, so I thought it was helpful to see the numbers."* (P10).

Dynamic assessments boost engagement: Participants expressed that answering the periodic quizzes made the experience more engaging, and the process helped them stay focused. P7 stated, *"I thought that it was a good tactic because if you were paying attention, and you're following along, there was no questions that seemed like extremely hard or extremely easy…they were like perfectly aligned with what she was explaining to you…And I thought that it helped me personally because as I went through, I knew that there was gonna be a question or a couple of questions after each section. So it kind of made me pay more attention while I was participating and helped me to better understand the material that she was trying to get through."* P09 also mentioned that the quizzes left her with more questions to think about, *"…they can give you a clue on what you should think after that topic. They can leave you with questions to think about."*

Dynamic adaptation personalizes the learning experience: All participants mentioned that they noticed some level of adaptation during the session, and they appreciated the amount of adaptation provided by Tanya. Participants felt they received educational content that was tailored based on their prior knowledge, which made the counseling experience more personalized and effective, e.g., *"I'm glad she didn't, you know, tell me about the stuff that I already knew, but she wanted to make sure that I did understand it."* (P4), and *"…she also did the quizzes, so she figured out what I knew and she didn't have to repeat what I already knew, it was nice."* (P13).

Several participants appreciated they were able to see more visual aids after they expressed their preferences during the conversation. P5 stated, *"I was able to have those visual aids…and also in a way, um, that was specific and individualized. For myself, that's great."* P7 described that she was a visual learner and particularly liked this feature, *"I really loved the choices that were given between like a verbal explanation or if you prefer to see this (with visual aids). Me, personally, I'm more of a... like I need to be a hands-on...kind of look, see, do-it-myself learner, so I really liked it there was that option."*

Increased awareness of breast cancer genetic risk: Talking with the virtual counselor successfully raised awareness of breast cancer genetic risk for our participants. Participants felt the discussion with Tanya prepared them for a future conversation with a healthcare professional. P11 expressed, *"…I was alarmed at the need to get, you know, breast cancer screening, which I think is a good thing, right? Like I think Tanya did her job in the sense that I'm a bit more wary of getting screenings earlier and just understanding really what the numbers might look like."* P10 also stated, *"I feel very informed…if I wanted to talk to a physician or genetic counselor, I think I would know the right questions and be prepared to like have that conversation with them."*

6 DISCUSSION AND FUTURE WORK

Results from both studies showed that the virtual genetic counselor was well accepted by the participants, and was effective in educating participants about breast cancer genetic risk. Qualitative analysis results of Study II confirmed that the implemented adaptive risk education was successfully acknowledged by all participants and effective.

For future work, we plan to implement a Prototype III, incorporating information processing theories into genetic counseling. In addition to challenges in communicating genetic risk, prior research also suggests that simply ensuring receipt and comprehension of risk does not necessarily lead to desired health behavior change, such as adherence to recommended medical guidelines [48]. In the past decades, several cognitive models of information processing have been applied to genetic risk communication [49, 50]. For Prototype III, we will apply the heuristic-systematic model (HSM) of information processing [51-53], a well-established and commonly used model explaining how individuals process persuasive risk messages, to genetic counseling, in order to effectively motivate at-risk individuals to adhere to prevention and detection guidelines for hereditary breast cancer. In addition to maintaining a dynamic model of the user's knowledge state and other user traits, the virtual counselor will also adapt to other constructs defined in the HSM.

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