It Is Your Turn: Collaborative Ideation with a Co-Creative Robot through Sketch

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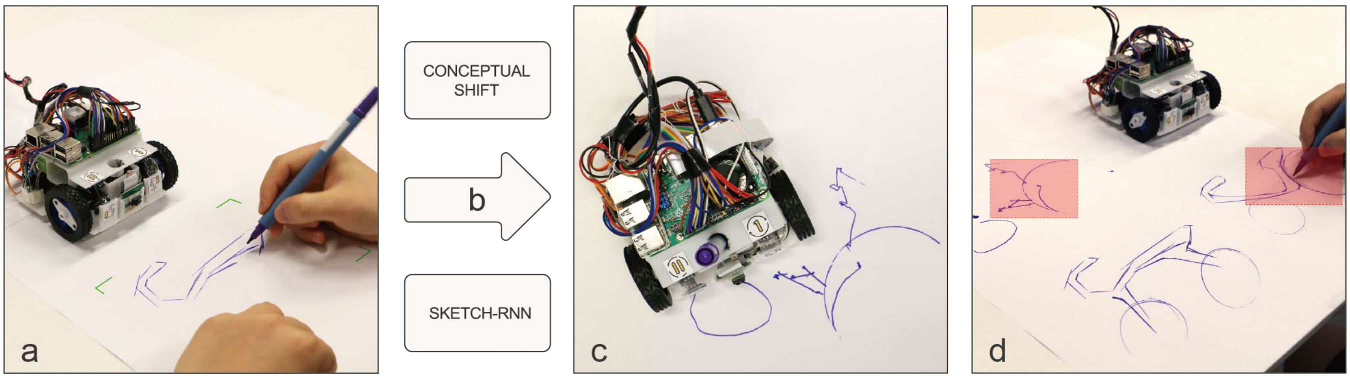

Figure 1. An overview of co-creating with Cobbie: a) the user sketches on paper and Cobbie captures the image (the region of interest is marked with rectangle boundaries); b) the co-creative system of Cobbie generates ideas according to the input sketch through conceptual shift strategy and sketch-rnn method; c) Cobbie is sketching on paper; d) the user continues ideating based on the sketch of Cobbie (marked with red mask).

ABSTRACT
Co-creative systems have been widely explored in the field of computational creativity. However, existing AI partners of these systems are mostly virtual agents. As sketching on paper with embodied robots could be more engaging for designers' early-stage ideation and collaborative practices, we envision the possibility of Cobbie, a mobile robot that ideates iteratively with designers by generating creative and diverse sketches. To evaluate the differences in co-creativity and user experience between the co-creative robots and virtual agents, we conducted a comparative experiment and analyzed the data collected from quantitative scales, observation, and semi-structured interview. The results reveal that Cobbie is more satisfying in motivating exploration, provoking unexpected ideas and engaging designers in the collaborative ideation process. Based on these findings, we discussed the prospects of co-creative robots for future developments of human-AI collaborative systems.

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Co-creative system; creative robot; early-stage design; ideation; human-AI collaboration.

CSS Concepts
• **Human-centered computing~Human computer interaction (HCI)**; *Collaborative and social computing devices*

• **Embedded and cyber-physical systems**; *Robotics*

INTRODUCTION
Co-creative systems are emerging with the advancement of artificial intelligence (AI), which involve AI and human collaborators in creating activities [1, 37]. As research has proved, people co-creating with other collaborators make unexpected and novel contributions that might not achieve individually [27]. However, individual creative thinking may be hindered in the human team due to social loafing or a resolute partner [21]. Unlike human partners, computational collaborators could reason about the intention of the users and stably present novel ideas with the user initiative. Nowadays, co-creative systems have been widely explored to effectively provide inspirations, provoke divergent thinking, and support innovation [37, 40, 44].

Co-creative systems usually allow the designer and a partner to take turns to create [1]. During this process, artificial agents are designed to inspire human creators through independent reasoning and dynamic ideation. For instance, Drawing Apprentice [11] is a web-based co-creative agent that analyzes the drawings from the users and generates unexpected sketches. In this paper, we focus on the co-creative conceptual design systems in the early-stage design period, which is open-ended and exploratory [21]. During the collaborative ideation, the shared sketch is considered as a significant representation medium to externalize the mental images of the designers and encourage discussions [39]. Therefore, our work exploits the previous definition of co-creative systems but on a specific design stage, collaborative ideation through sketch.

Our motivation is to explore the possibilities to integrate the co-creative technology into a physical robot and put collaborative sketching activities on tangible workstations. Despite present co-creative partners or other creative support tools [11, 25, 37] based on digital platforms such as computers or tablets, many designers insist on or get used to working with traditional physical drawing tools [49]. That's partly because digital tools could not capture and simulate the entire richness and variety of sketches on paper [36], which are necessary elements for designers to express their ideas. In addition, numerous attempts have been devoted to embedding AI systems into tangible and robotic interfaces. Early work has proved that projecting the user's workstation on a desk allowed users to take advantage of their naturally learned skills [50]. Later, Kwon and Kim [31] found that compared to interacting with a projection surface, people feel more expressive and friendly and have a desire for further interactions with a robot. Powers et al. [41] also discovered that the robot is more engaging and likable than the virtual agent. Based on these findings, we hypothesize that in the user-initiative co-creation, the robot that takes turns with designers to ideate on paper would be more helpful to provide novel user experience and support creative thinking, as compared to the virtual agent.

In this paper, we present Cobbie, an intelligent robot embedded with recurrent neural network (RNN)-based co-creative methods and mobile drawing system to support early-stage ideation. Figure 1 shows an overview of our co-creative systems where Cobbie provides inspirational sketches under the command of the designer. To understand the human-robot collaboration process and the differences between creating with robots and agents in user experience and design outcomes, we conducted a user study with both quantitative and qualitative approaches. Finally, we analyzed the process by which inspiration stimulation works and discussed the prospects of tangible interfaces and embodied partners in co-creative systems.

In summary, our paper has the following contributions in HCI and co-creativity community:

- We presented a novel intelligent robot integrated with the co-creative system to support collaborative ideation on paper during early-stage design.
- Through the user study, we evaluated the user experience and the ability at creativity support of the physical robot and the virtual agent in co-creative systems and analyzed their applicable conditions.
- We discussed the design implications of robotic interfaces in the field of human-AI collaborative systems.

RELATED WORK

In this section, we review previous studies to provide an understanding of co-creativity and the potential of co-creative robots in supporting conceptual sketch.

Co-creativity

Co-creativity is a rapidly growing field in designing creative systems and AI agents [1]. It has been applied in domains like musical coordination [42], public displays [34], education [30] and drawing [12, 37]. In the domain of design and art, several pieces of research have been introduced. Fan et al. [16] presented a web-based artificial agent, Collabdraw, to build a drawing together with humans, which demonstrated that computer systems could collaborate with human in real-time. Oh et al. [37] designed a prototype named DuetDraw, which draws pictures with users collaboratively, and further evaluated the influences of the initiative aspect in user experience. Also, Davis et al. [11, 12, 13] conducted a series of work to explore how co-creative systems better collaborate with users in creative tasks. They presented a co-creative design agent, Drawing Apprentice, which collaborates with users by analyzing their drawing input in a tablet and responding with real-time interaction. Karimi et al. [27] presented and evaluated a novel algorithm for the co-creative design system. In the above examples, users collaborated with co-creative systems via virtual agents.

Recently, some researchers have explored tangible interfaces of co-creativity. For example, Law et al. presented systems consisting of tangible interfaces [33] and robotic arms [32], to support human-computer collaborative design in the process of finding out an optimal solution by placing and arranging blocks of design components. However, design topics are usually open-ended and the differences of co-creating with physical robots and virtual agents are still unexplored. Therefore, we focused on sketch, a widely used method for designers to generate novel concepts and discussed the prospects of a wheeled drawing robot by comparing it with a web-based agent.

Computational Tools for Sketching

There are numerous computational tools for sketching such as [5, 15, 39, 44, 51]. They provided designers either powerful tools for creativity or inspiration in creation. For example, Painting with Bob [5] is a digital art creation tool for novice. DreamSketch [39] is an interactive 3D design interface to provide users multiple solutions. On the other hand, some research on user experience [23, 49] indicated that most designers still prefer drawing or sketching on paper in the early stage of work. Early work such as DigitalDesk [50] is an attempt to support computer-based interaction with paper documents. Work such as MouseLight [46] and PenLight [43] also demonstrates the prospect of working on paper directly. These efforts are attempts to bridge the digital and physical world via the technology of projection. Nevertheless, the researchers of [31, 41] pointed out that projection devices provide less emotional and friendly expression to users. To present a lifelike partner, we devised the co-creative robot that could interact and communicate with them through a variety of expressions.

Co-creative Robots

Challenges to create robots in the field of co-creativity are mentioned in [12]: (a) to perform well in an open-ended situation; (b) lots of requirements of the engineering knowledge. However, recent advances in AI and robotics [20, 29, 38] provided the possibility to embed the co-creative system into a robot. Today, robots are capable of interacting with users in a dynamic setting [18], perceiving the environment and completing tasks precisely [43] and contributing users' creativity [2, 17, 26]. Many studies tested the advancement of social robots, compared with virtual AI agents. Powers et al. [41] compared people's responses to an agent and a robot and concluded that agents and robots have the same social influence, while participants were more engaging when interacting with robots. Fasola and Matarić [17] introduced a socially assistive robot system aimed to motivate and engage the elderly in simple physical exercise. They conducted a comparative experiment and concluded that users displayed a strong preference for robots over agents. In the field of creativity, Robovie [26] is a robot that encourages users to generate creative ideas by asking questions and showing relating images or video to spur users into more creative solutions. Compared with the condition of PowerPoint presentation, Robovie could evoke more creative results. Based on these work that compared physical robots and virtual agents for social assistance and co-creativity, it is critical for a co-creative system to be thought helpful in reasoning and giving useful advice for designers, and capable to improve the co-creativity. Thus, in this paper, we presented a co-creative robot named Cobbie, not only for the friendliness of robots but also for the related improvement in human-AI collaboration and creativity.

COBBIE

We designed our research prototype as a creative and collaborative robot, Cobbie, with the purpose of generating inspirations and co-creating with users by drawing on paper. Given the literature research on co-creative systems and the theories for designers to get inspirations (discussed later in this session), there are some design principles. Firstly, we followed the previous definition of co-creation mode that human and the creative partner take turns to draw their ideas. Secondly, according to the discussions in [37], we give the dominant position to the user during collaboration. Also, we design some interesting movements and sound feedback as the communication "language" of Cobbie to indicate if users' actions took place. These interaction elements could strengthen its role as a human partner. Specifically, we devised three main human-robot interactions. Figure 2 illustrates an example workflow to produce a concept about bicycle with Cobbie.

Human-Robot Interactions

It is your turn

User could determine "when Cobbie should draw" by giving the pen to it. When co-creating with Cobbie, the user could define the iteration orders and the region of the paper to sketch. Once requiring assistance from the robot, the user can stick the pen into it. By selecting different pens, the stroke type could be controlled. Sensing the approach and departure

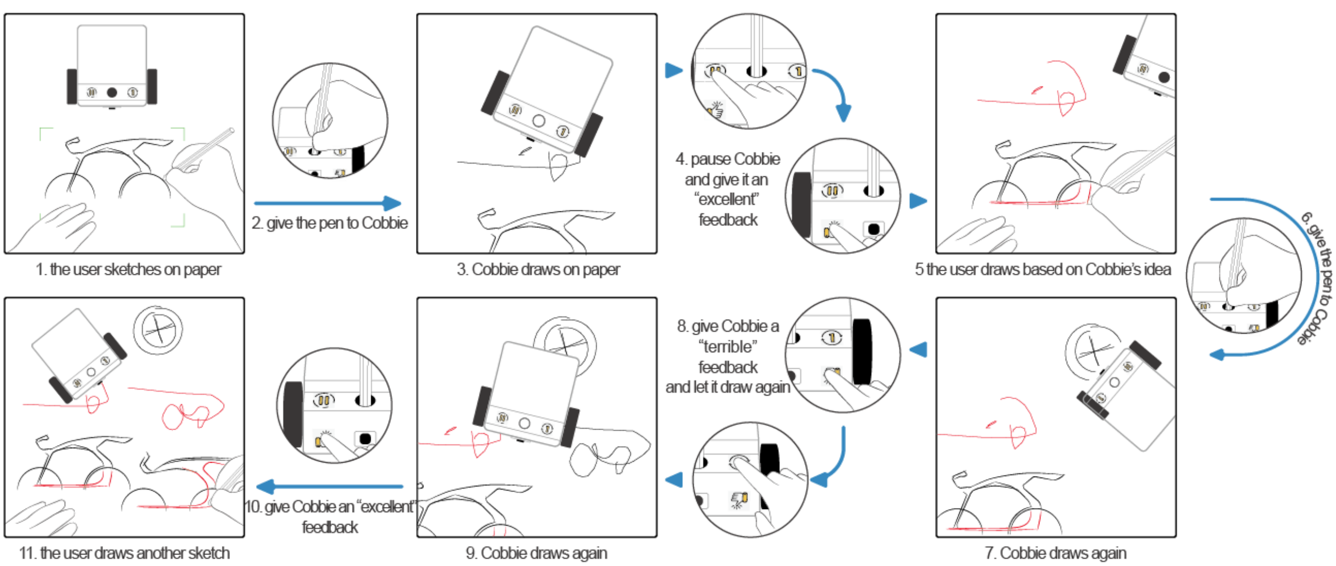

Figure 2. An example workflow of user-robot co-creation. 1) User draws the initial design concept of bicycle, 2) Cobbie captures the image at the time receiving the pen from the use, 3) Cobbie generates new sketches according to the captured image and draws it on paper, 4) User gets inspirations from Cobbie's sketches and suspend Cobbie with appraise, 5) User combines the sketches and draws a new idea with the bike frame of Cobbie's idea (shown as red lines), 6-7) Cobbie gets the turns to ideate, 8-10) User asks Cobbie to draw again and gives feedback, 11) User combines all the sketches and modifies the bicycle frame.

of user's hand, the robot will loosen the clipper, clip the pen, capture the sketch within camera range, adjust the distance between the pen tip and the paper automatically, move to a blank area of the paper and draw a diverse sketch based on the category and strokes of the input sketch. The inspirational source of Cobbie is the region it faces after the user inserts the pen, which can be manipulated by moving Cobbie. Therefore, the user can easily understand and select the input sketch within camera range, or the inspirational source of Cobbie. The sketch procedure begins and ends respectively with the sound of servos and buzzer.

Pause and Draw Again

User could stop or extend the drawing process of Cobbie at any time by pressing the "pause" and the "draw again" button. We hypothesize that the user may flash ideas when observing the sketching process of Cobbie. Thus, we devise this function to fulfill the nearly infinite variety and dynamism of the artistic intentions of users throughout their creative process [11]. In this case, the user can press the "pause" button to suspend the robot, take out the pen and record their sudden thoughts immediately. Meanwhile, therein lies another possibility that the user may get very few inspirations from the robot. In this situation, the user can press the "draw again" button and let the robot draw another one. A short sound from the buzzer comes out to confirm that a button is pressed.

Progressing with feedback

As we discussed above, the user may get few or many useful inspirations from the sketches drawn by the robot and the preferences of designers differ individually. Therefore, we devise two voting buttons presented by two icons (see Figure 1a) denoting "excellent" and "terrible" assessments to collect feedback from the user. The user could have different understandings with the level of assessments depicted by the icons, such as more moderate descriptors of "useful" and "useless". The user could vote when Cobbie finish or stop drawing. In this way, Cobbie can adjust the weights of candidate output types and thus provide more useful sketches. We added some expressive movements to Cobbie that it will move forth and back when it receives "excellent" feedback, and "shake its head" by rotating clockwise and counterclockwise when it receives "terrible" feedback.

Inspirational Strategies

We utilized the mechanism of conceptual shift [10] to inspire creativity, as it is a cognitive mechanism to aid the common creative process of analogical reasoning and has been identified for human-AI collaborative sketch ideation [27]. Specifically, conceptual shift could map the input sketch to another that has visual and semantic similarity [27]. With the association between them, trained designers could discover the previously unexplored aspects of the creative space.

Based on the conceptual shift, we made our prototype by selecting nine categories of three groups for demonstration and experiment. Each group has three categories one of which is the design topic and highly relating to the others (see Table 1). In our definition, taking the sketch of each topic as an input, candidate output sketch could be of the same class, a semantic extended class, or a visual extended class. Take "bicycle" as an example, candidates may be bicycle, wheel and skateboard, as wheel has semantic relation with bicycle while the abstract sketch of the skateboard is visually similar to that of the bicycle. We reconstruct the input sketch by interpolating with a randomly selected sketch from the output category. We initialize the weights of three output categories as the same. Weights change with the user's feedback during use.

Topic	*Semantic Extension*	*Visual Extension*
bicycle	wheel	skateboard
eyeglasses	eye	peanut
wristwatch	clock	bracelet

Table 1. Selected topics and the corresponding associated classes with semantic or visual similarity.

IMPLEMENTATION

We made a prototype of Cobbie according to the interactions and principles above. In this section, we detailed the robotic system and the idea generation system that ensure Cobbie's inspirational sketch functionality while interacting smoothly and effectively with the user.

Overview

The implementation of Cobbie is mainly due to stroke-3 format [19], which represents the hand-drawn sketches as a sequence of motor actions controlling a pen: which direction to move, when to lift the pen, and when to stop drawing [22]. This vector representation can be the input and output of all the algorithms we use and directly used as the pen tip trajectory and actions of the robot.

The general flows are illustrated in Figure and as bellows.

- Cobbie uses a CSI camera to capture bitmap pictures, which is processed and converted to the stroke-3 format.
- Cobbie classifies the input sketch into a category and selects an output category according to the weights of inspiration strategies in the former section.
- Cobbie calls the corresponding generative model and generates the output sketch represented as strokes, which are transferred as Cobbie's kinematic actions.

Robotic System

Cobbie is composed of a central controller Raspberry pi 3B+ and its peripherals including the camera, user interface, pen holder, and locomotion subsystems. All components come together as seen in Figure with a 3D printed architecture designed to be easily graspable. A fully assembled robot measures 118×80×30 mm.

Penholder. Like most of the drawing robots, the pen is installed in the middle of the wheels. As we use the stroke-3 format to represent the trajectory, this installation is suitable. The pen holder is a pair of mechanical arms with two servos to clip and lift the pen.

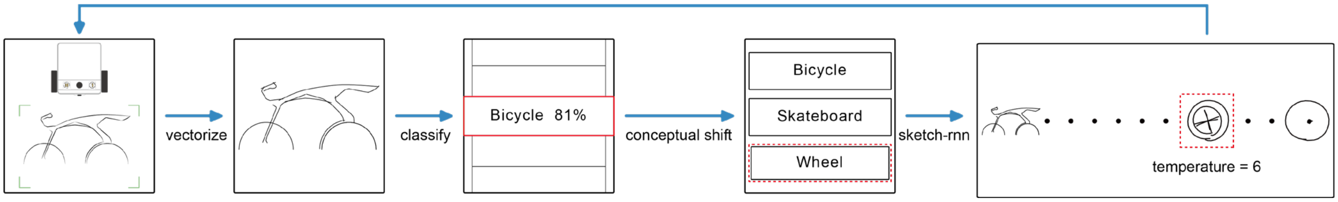

Figure 3. Algorithms of idea generation method: 1) preprocess the input bitmap image into stroke-3 format, 2) classify into a category, 3) select a sketch-rnn model from the candidates of the same, visually similar and semantic related categories, 4) interpolate between the input sketch and a random sample in dataset, 5) output the 6th in nine sketch as stroke-3 format, or the action sequences of Cobbie.

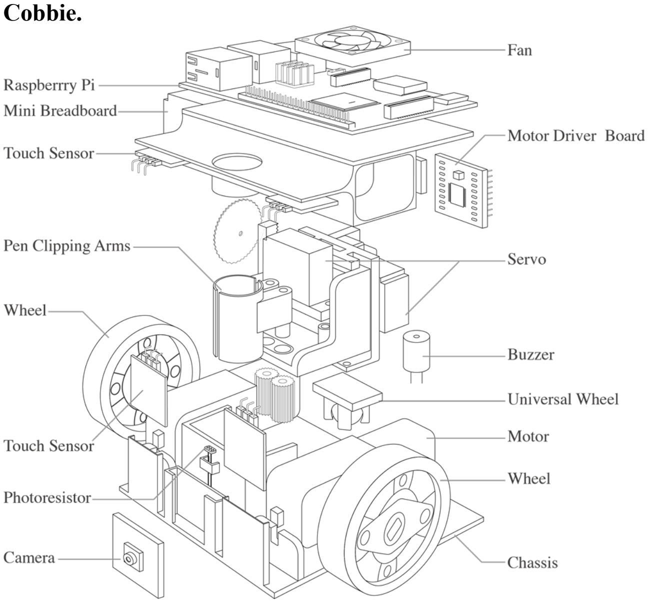

Figure 4. Exploded view of Cobbie, upside-down.

User interface. The robot has four capacitive touch buttons on the top and front surfaces that receive real-time feedback and motion instructions. A photoresistor is beside the pen holder, which is in parallel with a 2,000-ohm resistor in the circuit. When the user reaches out the hand to fetch the pen and block the photoresistor, the light intensity decreases. Therefore, when the resistor value is higher than 2,000 ohm, the clip servo rotates and releases the clipper. A Piezo Buzzer with a low sound is installed to indicate when the user presses any button or Cobbie finishes drawing. The sound of servos can also serve as an indicator for starting drawing.

Locomotion system. The Wheeled mobile robots are commonly used platforms in drawing applications for the advantages of small size, large workspace and portability [30]. Our construction of the locomotion system is based on a classical differential drive chassis with the single universal wheel in the back of the robot. It's driven by two motors with an open-loop control through a driver board. It's powered by a 6V lithium battery. To reduce weight, the battery is placed outside and the wire is tied with the raspberry pi's power cord, extending vertically to reduce resistance to movement. Of the same data format as stroke-3, the robot can 1) change direction of motion when one wheel moves forward and the other wheel moves backward, 2) stroke a straight line when two wheels move forward and backward together.

Camera. The camera is installed with an angle of 10° from the vertical plane and can take pictures with a range from 2 cm to 40 cm at length and 20 cm at width in the front. We intercepted a relatively clear region of 20×20 cm at a resolution of 2544 ×1988.

Software System

We adapted sketch-rnn model [22] to address our objectives to 1) express a sequential, vector representation of an image as a set of pen stroke actions; 2) reconstruct an input sketch and generate a vector image. Also, we use the RNN-based recognizer of Google's quickdraw game [24] to recognize the object category that the user tried to draw. The generation and classification models are trained based on Google brain's quickdraw dataset [24], in which we selected nine categories. All the models are embedded in Raspberry Pi thanks to Tengine [53].

EVALUATION

To test the user experience and co-creativity of our prototype, we conducted a user study with a co-creative agent as the control condition. We explore how designers experience with two co-creative collaborators during early-stage design ideation, the resulting concepts, and the system usability.

Participants

We recruited 16 participants from the local designer town (6F, 10M, mean age = 24.06, SD = 2.38). They are designers and design students with at least 2 years' design experiences (M = 4.63, SD = 1.67). All of them have never used any co-creative tools but usually searched online for inspiration in the early stage of design practices, their expertise covers product, interaction, and graphic design. See Table 2 for detail information. In addition, we recruited 2 designers with at least 7 years' design practices in the field of industrial and graphic design to assess the design outputs in our study. All participants were reimbursed $10 for their time.

Study Design

The study had a within-subject design, with participant ideating about a design topic using each of two sets of the system (Cobbie and a web-based agent, we named it as Cogent). Cogent is a JavaScript page sharing the same systems, interactions and functions with Cobbie, as well as similar drawing speed. In the control condition, all tools include a laptop with the web page opened and a Wacom digital panel, while in the experimental condition, participants were provided Cobbie, an A3 paper and a pen.

Each condition was treated as a single design activity, where participants developed and expanded a design concept using Cobbie or Cogent. We posed two design topics with sufficient creative freedom: 1) wristwatch and 2) eyeglasses. To prevent carryover effects, the orders of design topics and conditions were counterbalanced.

ID	*Age*	*Gender*	*Area of design*	*Years of practice*	*Education*
P1	24	M	Industrial	5	MA
P2	25	M	Industrial, Graphic	7	MA
P3	30	M	Industrial, Engineer	5	PhD
P4	21	M	Industrial	2	MA
P5	29	F	Industrial, Interaction	8	PhD
P6	22	M	Interaction	4	MA
P7	23	M	Interaction	4	MA
P8	22	F	Industrial, Interaction	4	MA
P9	24	M	Graphic	6	MA
P10	24	M	Industrial	5	MA
P11	24	F	Industrial, Interaction	5	MA
P12	24	F	Graphic, Interaction	5	MA
P13	24	F	Industrial, Interaction	5	MA
P14	23	M	Industrial	2	MA
P15	24	M	Interaction	2	MA
P16	22	M	Industrial, Interaction	5	MA

Table 2. The detail information of participants.

Procedure

The study was conducted in a small conference room. Each condition began with an overview of the design task and the functions of the using system for 5 minutes, followed by participant finishing four tasks: 1) insert the pen into Cobbie or press the "start" button in the interface of Cogent; 2) stop the drawing process of Cobbie or Cogent; 3) give a feedback to Cobbie or Cogent; 4) ask Cobbie or Cogent to draw again. To prevent preconceived notions of how to use it, we devised these tasks to make them get used to the basic operations without involving creating orders or design contents. The design session lasted for 15 minutes and there was a 30-minute interval between conditions. During the design, one observer was recording the behaviors of participants.

Data Collection

We recorded a log of participants' operation to help us observe user activities during the design tasks. All the conditions were also video-recorded for interviews and discussions with participants. After each design session, participants filled out a visual analog scales (VAS) to rate their experiences and design outcomes. The final concepts are classified and evaluated by two design masters.

Self-rating Questionnaire

According to the USE questionnaire [33] and the Creative Support Index (CSI) [6], we designed a VAS scale to quantitatively evaluate Cobbie and Cogent from eight dimensions: 1) Ease of use, 2) Ease of learning, 3) Friendliness, 4) Engagement, 5) Usefulness (of the inspirations), 6) Satisfaction (of the quality of design outcomes), 7) Creativity, and 8) Efficiency. Each dimension has 3-5 detailed items. The 1-4 dimensions measure the user experience and the rest measure creativity support effects.

Semi-structured Interview

We also conducted 30-minute semi-structured interviews with audio recording. The participants were asked to describe their design experience and final concepts, and then some questions based on our observational scripts about how they co-created with the AI partner including some issues they encountered during use, and how they give feedback and receive responses. When the participant forgot some details, we watched the videos again. Finally, we transcribed the record and got qualitative scripts.

Rating for Ideation effectiveness

Each final concept is rated for quality and novelty by two experienced designers. We showed the description of two rating items and the participants' self-reported final concepts (in *supplementary materials*) in a randomized order. They were asked to rate as either 0, 1, or 2 representing poor, ordinary and optimal degrees. The novelty of a design is how unconventional or unusual an idea is compared to other designs, within the set of designs generated within the experiment [18], while quality measures the feasibility that the concept can go further in the next design stage.

RESULTS

We report results from statistical testing and observations from behavior and interview data. Examples of iterative sketches created in the study are shown in Figure 5. First, we present the quantitative results, as they frame the primary conclusions of our study. Next, we analyze the post-study interview and participants' behaviors during co-creation to explore detail activities, feelings and interactions.

Quantitative Results

For each dimension of the VAS scales, we illustrated the data distribution by box-plot in Figure 6. As the lines of medium values indicate, Cogent is rated higher than Cobbie in efficiency, while in the other dimensions, Cobbie is rated higher. The distances between the upper and lower lines of quartiles show that the variance of the ratings was greater for Cogent in most dimensions except for usefulness, friendliness and efficiency, in which the differences in the latter two are not obvious. Using two-way repeated-measures ANOVA for VAS scales, significant difference is observed between conditions for satisfaction, creativity improvement, friendliness and engagement. However, there is no significant difference in ease of use, ease of learning, efficiency and usefulness of inspiration. From the perspectives of the users, they feel satisfied with the co-creativity outputs although the inspirations work in the same way. Moreover, a significant difference is observed between items in ease of use and creativity improvement. We used two-sample t-test in creativity improvement items and only the exploration item ($t=3.35$, $p=0.002 < 0.1$) is significant. In effortlessness, immersion and enjoyment, there is no significant difference.

The results of the evaluations for ideation effectiveness are illustrated in Figure 7. To get a sense of the degree of consistency between design masters, we compute the intra-class correlation coefficient across all ratings and get an acceptable correlation (ICC = 0.71). We use Wilcoxon rank sum test with continuity correction and the results reveal that ideating with Cobbie generated designs of significantly higher novelty than with Cogent when designing eyeglasses ($t = 1.80$, $p = 0.06 < 0.1$). As for quality, experimental condition and control condition have no significant difference. Additionally, there is a high degree of variability in idea content and quality between topics and subjects. It shows no significant difference when designing wristwatch, although the frequencies of the scores still indicate that in each topic the design outcomes with Cobbie are evaluated higher in both the quality and novelty aspects.

Qualitative Results

Getting inspirations from the Process

Participants were inspired by Cobbie from several aspects: 1) lines and sketches with variable strokes, 2) the movements, and 3) the interactive process. In contrast, participants mostly got inspirations from the final sketches of Cogent. We noticed one word that was mentioned most frequently by the participants when talking about co-creating with the robot: "*unexpected*". They said that these distinctive strokes drawn by the robot activated their minds and brought them so many unexpected instantaneous inspirations. For example, P2 shared his design of the geometrical watch. He said, "*This straight line might be a mistake of the robot. However, it reminded me of stylistic art and gave me such an unexpected inspiration*." Moreover, some participants drew inspirations from the movement of Cobbie. For instance, P9 said, "*When I was waiting for the robot to draw, I suddenly felt the passing time, and I turned this feeling to the dial design.*" Different from the robot, most participants thought that the inspirations got from the agent were straight and simple. P1 and P4 said that sketches drawn by the agent were accurate, and helped them ideate directly. However, 7 participants claimed that they didn't get diverse inspirations from the agent. For example, P9 said, "*Watching the agent drawing, I cannot think in the way as collaborating with the robot.*" P12 also said, "*Unlike the flexible strokes of the robot, lines drawn by the agent provided fewer inspirations.*"

While based on our current results, the influence age could have on co-creative systems is not obvious, we observed the trend that participants may require different inspirations due to occupations and year of design experience. Novice designers required more basic and initial inspirations, while experts preferred clear ideas, considering the productivity of a design task. Even the same participant had different demands in different stages of design. Although our design tasks are coming out with a design concept. Some participants have the desire to step forward and get more inspiration for the next design stage. P2 and P6 mentioned that the robot should have the capability to adjust its performance to fulfill different demands in different stages of design.

Overall, while collaborating with Cobbie, participants not only combine the ideas but also focus on and enjoy the process, thus the ideation quality varied.

Improvement in Co-Creativity

The sketches from Cobbie and Cogent successfully make designers associate with the styles or dynamic effects in memory, resulting in visual and functional innovations. Participants liked to figure out why Cobbie "think like that" while these thoughts never happen when facing Cogent. As a result, the sketches from Cobbie provoke a greater degree of re-interpretation and foster creative thinking from different perspectives. For example, P1 said, "*Both the robot and the agent kept me thinking and associating*." P4 said, "*These sketches reminded me of some novelty shapes of eyeglasses, and fostered me ideating irrationally*." Although P6 and P13 pointed out that the sketches drawn by Cobbie and Cogent were abstract, it was these lines, which were different from figurative ones, gave them diverse inspirations by developing them thinking from different perspectives. P3 also said, "*I was looking at the robot drawing abstract paintings, and many fresh ideas came into my mind*." Thus, P7 and P16 said that the system allowed them to inspect their sketches from the perspective of the machine, which might not be available when collaborating with human-beings. In contrast, P5 and P14 thought that they got few inspirations from neither the robot nor the agent. P5 said, "*I wished to get some inspirations of the structure of the watch, but these abstract lines helped me little*." P14 gave a similar point of view.

As for the design content, we asked the participants to classify their concepts into functional innovation, styling innovation or both. Functional innovations are inventing new sub-functions into design topic, while styling innovation indicates integrating new style into the shape. There is an apparent trend that Cobbie helps to promote creative dynamic ideas in function compared to Cogent, which is "*more difficult*", as P16 and P8 said, and one participant (P4) even generate an idea with both stylish and functional innovation with Cobbie.

Collaborating with an AI Partner

Participants collaborate with Cobbie and Cogent in different manners. A somewhat surprising finding is that two participants not only co-created with the robot but played with it. P8 and P12 only drew some simple lines at first and then let the robot drew over again and again. Sometimes they even interfered the movement of the robot. P12 said, "*I did not have any ideas when I received the task, so I decided to let the robot draw something at first. I changed the position of the robot deliberately to make these sketches overlapped*." Similarly, P8 said, "*I wondered what the robot would draw if I interfered. Surprisingly, these sketches looked like a smiling face that reminded me of a wonderful idea. I designed a pair of glasses that can reflect people's*

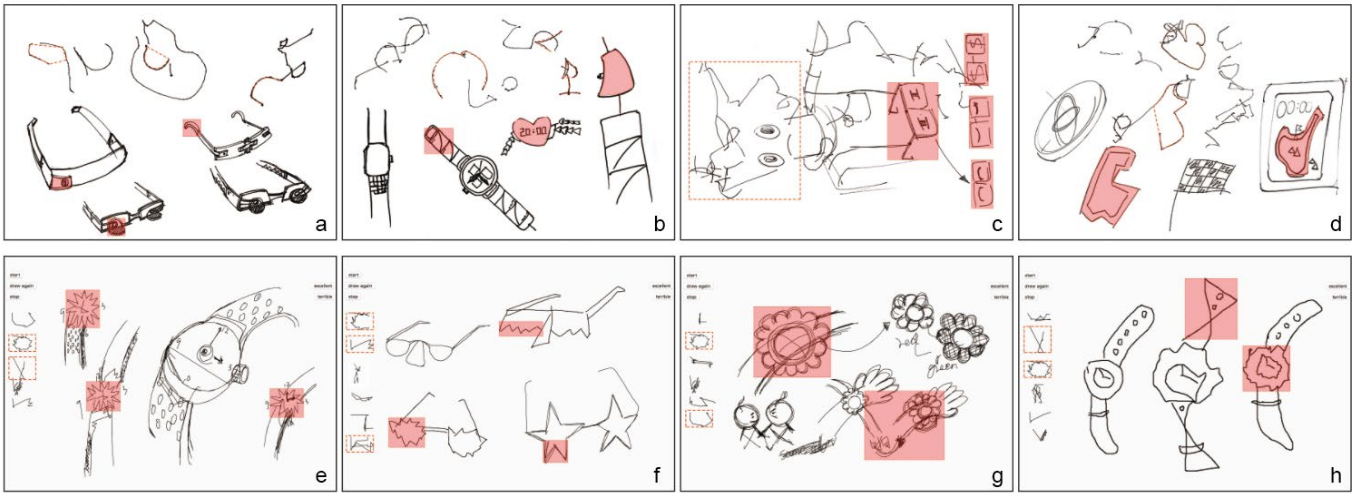

Figure 3. Examples of design sketches from participants when co-creating with Cobbie (a-d) and with Cogent (e-h). Selected examples cover almost all the conditions: 1) Iterating for 3-6 rounds; 2) Participant changing ideas all the time (a) and iterating on the initial idea (g); 3) Taking turns to sketch (f) and one drawing more sketches (c); 4) User drawing in the blank area (b) and complementing the sketch of Cobbie (c). Participants were inspired by sketches drawn by the robot or the agent (marked with red boxes).

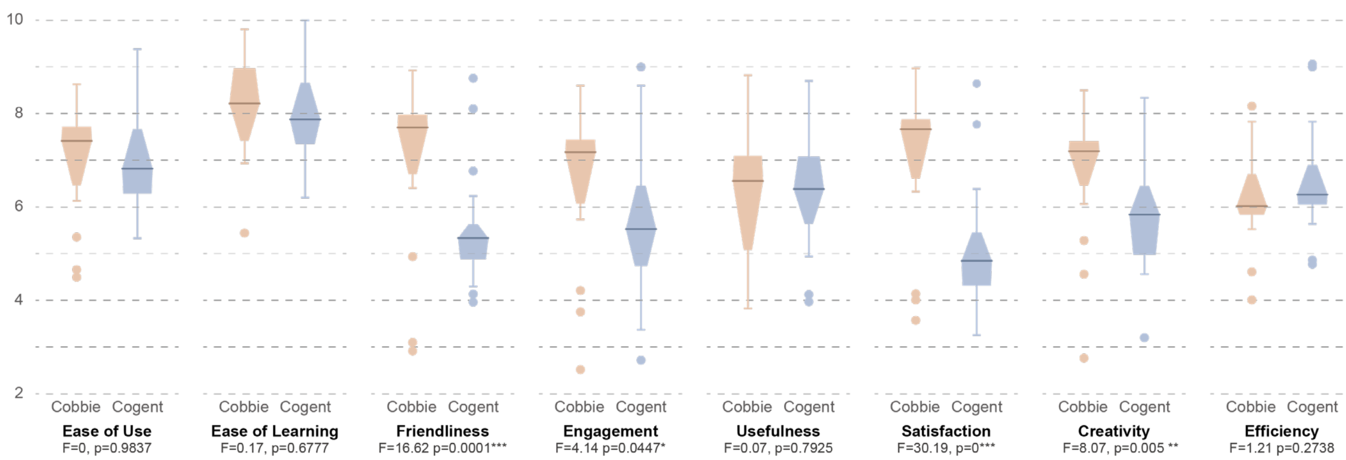

Figure 4. Box plot with the data distribution and the result of two-way repeated-measures ANOVA for participants' self-rating. Significant difference is observed between conditions for the satisfaction, creativity improvement, friendliness and engagement, except for ease of use, ease of learning, efficiency and usefulness of inspiration. Statistically significant results are reported as $p < 0.001$*, $p < 0.01$**, $p < 0.05$*).**

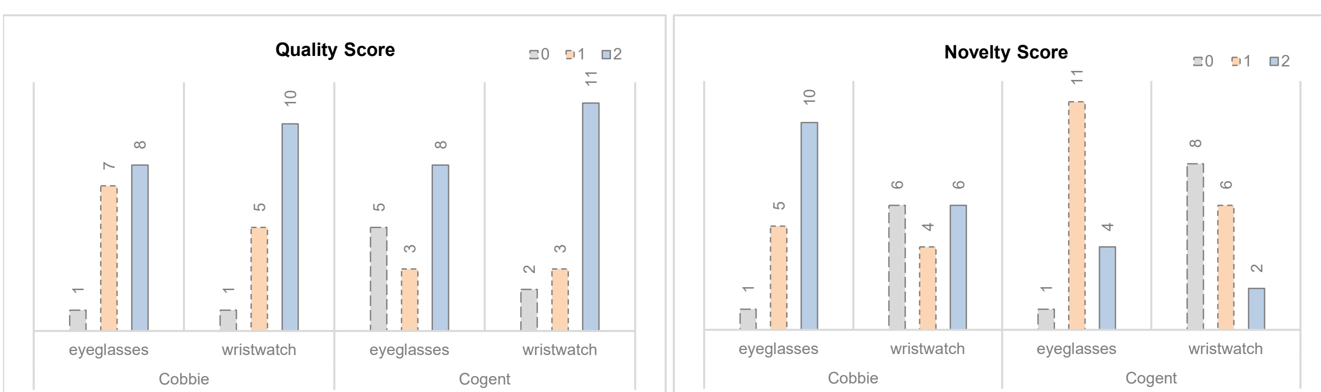

Figure 5. Frequency of quality (left) and novelty (right) ratings for the final design concepts.

emotions." Generally, participants considered the robot as a partner in their tasks, while treating the agent more as a tool. Through the interview, we identified the following reasons: 1) the movement and interaction of the robot are interesting, 2) mistakes of the robot in the process of drawing make it more lifelike. For example, P8 said, "*It was amazing I could communicate with the robot emotionally, I felt I was collaborating with a true partner.*" P2 said, "*Even the sound the robot made had a mechanical rhythm*." P12 also said, "*The way I collaborated with the robot was similar to my colleagues, it could even express its disappointment to me.*"

Moreover, participants such as P8 and P16 said that they enjoyed sharing one pen with the robot, liked they were discussing. Compared with the robot, many participants saw less emotion on the agent. They pointed out that the agent drew sketches accurately and mechanically, which made them instinctively treat the agent as a tool. For example, P3 said, "*lines drawn by the agent were accurate while missing the diverse strokes of lines.*" P16 also said, "*I had a strong feeling that the agent was the same as the software we used before, I knew these lines were generated by the programs.*"

In addition, some participants said watching the robot drawing was very interesting, and they enjoyed the progress. However, waiting for the agent to draw made some of them anxious because they thought a tool should be productive and present the whole sketch immediately.

Expectation
As designers, 11 of 16 participants had a strong desire to share their suggestions about the future developments of Cobbie and Cogent during the interviews. As have mentioned above, a ubiquitous version for more design stages is required, such as "*to produce more detail solutions*". In addition, they have envisioned functions and interactions with Cobbie. P8 and P12 imagined the addition of gesture interaction module. P16 preferred to communicate with Cobbie by voice interaction systems. As we can see, multiple modalities of interaction can better meet participants' imagination and expectations for the future development of Cobbie. On the other hand, although the robot expanded their mind, some participants thought co-creating with the agent could be more concentrated, which was essential for designers, too. P10 said, "*The robot was interesting, while less productive.*" P16 said, "*Thinking from different perspectives also means unfocused*."

System usability
We found that all users could learn to use the systems after finishing the training session, as they require fewer operation steps and types.

During the experiment, we noticed that the "pause" button of Cobbie was seldom used. Reviewing the process of tasks through recordings, we identified only P8 and P12 used the button when co-creating with the robot, while six of them used the button of the agent. When co-creating with the robot, many participants said that the robot was too big and blocked their view. They had to wait until the robot finished to have an overview of the sketch. Some participants complained that although they wanted to press the "pause" button, sometimes the robot was backing to them and made the button hard to touch. For the agent, participants said the reason that they did not press the "pause" button was that sketches drawn by the agent were regular and rigid. In contrast, 12 participants had pressed the "draw again" button. Reasons differ. Sometimes they pressed the button because sketches brought few inspirations to them. Sometimes they felt excited about another inspiration.

We also examined the user experience of the feedback button of the two tools. Overall, most participants liked the way of interacting with the robot and received positive feedback from it. This kind of communication not only makes the robot friendly and lifelike but also adjusts weights of parameters of the algorithm naturally. However, P5 said, "*The feedback when I pressed the buttons were not clear, I thought the robot was still working.*" On the other hand, few participants used the feedback buttons of the agent. P9 said, "*I did not think the agent had understood me.*" P14 even said, "*I felt the two buttons were placebo*", as they use Cobbie and Cogent for only 15 minutes with about 3 rounds of iterations, the adjustments of inspiration strategies didn't work apparently. When asked about the noise, most participants thought the sound of the robot had little effect on them during the experiment but maybe annoying under long-time exposure.

DISCUSSION
Our experiment combined quantitative and qualitative methods to investigate the impact of the embodied robot in providing inspirational stimuli on ideation during conceptual design. Both visual analog scales and effectiveness evaluation show that Cobbie appeared more friendly, engaging and helpful to explore new design space and produce creative outcomes for designers in generating ideas, though Cobbie and Cogent provide similar inspirational stimuli. The semi-structured interview provides a more detailed account of our findings. We discussed the implications of tangible and embodied robots in human-AI co-creative systems and the limitations of our work in the section.

Prospects of Tangibility and Embodiment
The tangibility and embodiment of the co-creative robot are the motivations of our research. The results of self-rating VAS scales, observational data and statements in the interview all indicate most participants treat the robot as a partner and the agent as a tool. Consistent with the findings in [31], robots are more friendly and engaging than agents, especially as companions with human. Specific to Cobbie, that's because of its dynamic movements and multi-modal interactions as compared with the flattened interface of the screen-based Cogent.

In the co-creative system, embodiment makes it easier to map the AI creator to a specific metaphor. That confirms the findings in [32] that robots cause social interpretation and responses from users. During this process, the user could start up a new way of thinking, that is, to understand and adopt what the robots are thinking about, which usually happens when collaborating in a human group. Therefore, as we have seen, although both the robot and the agent are capable to provide inspirational sketches, the robot better stimulates the user to think from diverse perspectives. In this way, collaborative thinking works.

Application Conditions

As the results show, users' preferences for co-creative robots and agents vary with working conditions and their experiences. Experienced designers have less tolerance for reaction time and errors, which mostly happened to the robot. In contrast, novice designers usually neglected the time they spent and like to wait for an unexpected thought. Therefore, efficient agent relatively suits experienced designers and novice prefer the playful and educable robot. However, our subjects are mainly in their twenties, so there is no obvious correlation among their ratings, design experience and age, which is an interesting direction of future exploration. One possible hypothesis is that younger designers might be more used to interacting with Cobbie, as some participants enjoy playing with it, while the attitudes of elderly users towards Cobbie may be more negative unless they perceived it with higher level of personal association [[8]]. The application conditions also differ with the habits of the designer. As most participants claimed, they get used to ideate on paper and in this way they could be more productive, while there are also some participants prefer drawing with digital tools.

Although Cobbie has been evaluated as effective to reason the input image, generate reconstructed sketch and communicate with the user through movements and sound, there are still various constraints. Despite no significant difference in efficiency, reaction time, occasional errors and noise could interfere with the progress, as stated in the interview results. Moreover, co-creating with the robot has more requirements for the environment. Comparatively, the on-screen agent can be used in various digital platforms and sketch accurately. Therefore, there is tremendous space for the development of Cobbie through the improvement of both the hardware and software systems. For example, it could be better to partition the robotic system into modular components of a tiny drawing part, interactive part and central processing part. In this way, we could reduce the areas blocked by the robot, improve the processing speed, and allow for more interactive interfaces. Also, there is also some design space for co-creative agents. For example, adding interesting elements and vivid responses on the screen, as discussed in [37], could strength the metaphor as a partner and improve the co-creativity.

Limitation and Future Work

Except for the prospects and deficiencies of the co-creative robot and agent, we also discovered some limitations in our study. Firstly, the duration of the experiment is not long enough for the system to progress with the user's feedbacks and thus lack the observation of long-term companionship and cooperation. Secondly, Cobbie and Cogent cannot represent all the co-creative systems although we have got some credible findings with our prototypes. Thirdly, as the results show, the design topics also have an impact on the co-creative outputs and we should test a variety of design topics. Thus, because the abstraction of a sketch can aid in the creative process [27], the expressiveness of Cobbie and Cogent were controlled such that they would be approximately the same, which may have affected the fairness of the comparison between them. Therefore, further research should explore the impact of expressiveness on such creativity support tools.

Many participants in our user study shared with us their expectations and suggestions for co-creative robots, such as interactive interfaces in more modalities and a ubiquitous version for more design stages. According to their suggestions and our discussions, we will adjust both the design of the robot and the algorithm of the co-creative system to improve its performance in the co-creative system and support extended modules. We will also explore scaling the Cobbie system to other cognitive mechanisms, research other design stages as well as other age populations, and investigate other human-robot collaboration modes that may be more effective in the future. During this study, we get some new ideas of more patterns of human-robot co-creation like the collaboration between a human group of designers and one assistive and creative robot, and we plan to explore that in future work.

CONCLUSION

In this paper, we envisioned the possibility of a co-creative robot that can iteratively ideate with human by generating creative and diverse sketches and presented Cobbie. We proposed the design and implementation of the interaction, inspiration mechanism and mobility system. A comparative study is conducted with another prototype as a web-based co-creative agent. The quantitative and qualitative results reveal that Cobbie performs better in provoking exploratory thinking and engaging designers in collaborative ideation, while the agent has clear expressions and supports various working conditions. Based on these findings, we discussed the prospects of the tangible and embodied robots in human-AI collaborative system design.

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