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Are Space-making Robots, Agents?
Investigations on User Perception of an Embedded Robotic Surface

Yixiao Wang, François Guimbretière, and Keith Evan Green, *Senior Member, IEEE*

***Abstract*—Novel, "space-making" robots have potential to redefine physical space and the human activities occurring in it. Categorically distinct from many robots and far removed from humanoids, space-making robots are not objects in space, not anthropomorphic, not animal-like, not mobile, but instead, integral with the physical environment, embedded in or forming walls, ceilings, floors, partitions, vehicle interiors, and building envelopes. Given their distinctiveness, space-making robots offer a novel human-machine interaction. This paper investigates whether users perceive space-making robots as agents—artificial social actors characterized by the capacity for intelligence, recognition, and intention. Results of an in-lab experiment with 11 participants and an online, between-group experiment with 120 participants show that people attribute agency metrics of *intelligence, intention, recognition, cooperation, collaboration, friendliness,* and *welcome* to our reconfigurable robotic surface embedded in a wall partition. While space-making robots may become numerous in the built environment, our results are significant, moreover, for their broader implications for conceptualizing and designing human-machine interactions.**

I. INTRODUCTION

Robots characterized as space-making have emerged, beginning in the late 1990s. *HypoSurface* (Goulthorpe, MIT, 2003) is an interactive screen-wall using electromagnetic actuators that physically reconfigures in response to audio, internet, and human-motion inputs [1]. *InteractiveWall* (Hyperbody Group, TU Delft, 2009) is an interactive wall designed following the concept of "Emotive Architecture" whereby the wall reflects people's physical presence, in real-time, via movement of mass, lighting, and projections [2]. The *Animated Work Environment* or "AWE" (Green, Clemson University, 2007) is a robotic work environment—a robotic display wall and mobile worksurfaces—that reconfigures to support changing work needs based on user activity and preference [3]. These robots share the following characteristics (1) they are physically far larger and more imposing than a person; (2) they are not objects in the environment as much as they shape the environment; (2) they, as space defining, provide novel affordances (e.g. altering the atmosphere of the space; giving form to human activity); and (4) they are interactive and may be intelligent (or perceived as such). The authors define this kind of robot as "space-making."

Our concept for the human-machine interactions of space-making robots—how people interact with them and how they are perceived by humans—is informed by two interrelated design-research paradigms: *Computers Are Social Actors* (CASA) and *Human Agent Interaction (HAI)*

A. "Computers Are Social Actors" (CASA)

The research paradigm *Computers Are Social Actors* (CASA) is a well-established theory extensively studied by design researchers [4],[5],[6]. In the CASA paradigm, non-humanoid robots are designed as if they have the capacity for recognition and intention [6]. For one, the lamp robot "Kip1" [7] with a "head" and a "torso" is designed as a conversation companion that reacts to the volume of the human voice through its movements as if it understands the context of human, conversational exchanges. Another example, the mobile, robotic "mechanical ottoman" [8] exhibits carefully designed movements that encourage people to use it to support their legs or as a stool. Space-making robots is an interesting, related case as they are categorically non-anthropomorphic and yet may be perceived as social actors [4].

B. Human Agent Interaction (HAI)

The research paradigm Human Agent Interaction (HAI) like CASA is well established in design research, both as a theoretical foundation (e.g. [11],[12]) and in informing empirical studies (e.g. [7],[8]) in both the HCI and HRI communities [6]. Core to the HAI paradigm is its definition of "Agent." Through this theoretical lens, in the context of HCI research, Norman emphasizes that an "agent" is defined as both social and intelligent [11], and Cassell defines "agent" as an interface or, more broadly, a computational system perceived as a person [12]. Similarly, Osawa and Imai argues that a system is only an "agent" when it is perceived as one (i.e. an "agent," perceived by users as an artificial, social actor) [10]. From HRI research, Sirkin et al. use the constructs of "perceived recognition" and "perceived intention" to measure if a nonhumanoid robot is considered "alive" by users [8].

As informed by CASA and HAI, the two experiments reported here borrow, in particular, the definition of "agent" from Osawa and Imai, an "agent" defined as "an artificial social actor that is accepted by users through her/his intentional stance, based on Dennett's Intentional Stance [13] of "whether users are conscious or unconscious of the fact" [10]. The authors employed this particular definition of "agent" as this definition encompass the key elements that define agency as proposed in [8],[10],[11],[12]. From CASA and HAI, we offer these three conditions for attributing agency: (1) an artifact is only an agent when it is perceived as such by a human; (2) an "agent" is characterized as intelligent, recognizant, and intentional; and (3) an "agent" is social.

By way of two lab studies, this paper investigates whether users perceive space-making robots as agents—artificial social actors characterized by the capacity for intelligence,

Yixiao Wang is with the Department of Design + Environmental Analysis, Cornell University, Ithaca, NY 14853, UA (510-529-8905; yw697@cornelll.edu).

Keith E. Green is with the Sibley School of Mechanical and Aerospace Engineering, Cornell University, Ithaca, NY, 14853, USA (keg95@cornell.edu).

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recognition, and intention [10]. Our results have implications not only for this novel typology of robots but more broadly for conceptualizing human-machine interactions and intelligence.

II. PREVIOUS RELATED WORK

Space-making robots are related to previous related work with respect to three areas of inquiry: non-humanoid robots designed and studied by the HRI community, Architectural Robotics, and Shape Changing Interfaces.

A. Non-humanoids in Human Robot Interaction (HRI)

Typologically, space-making robots are nonhumanoid and yet distinct from many nonhumanoid robots developed and studied by the HRI community, in three respects. Firstly, many of the nonhumanoid robots of HRI research are, to a degree, made to look anthropomorphic (e.g., "Kip1" [7] mentioned above), whereas space-making robots are not. Secondly, many of the nonhumanoid robots of HRI research are mobile (e.g., the "mechanical ottoman" robot [8] mentioned above), whereas space-making robots are not. Thirdly, most of the non-humanoid robots of HRI research are objects [6], while space-making robots are integral to the physical environment (i.e. embedded). These differences may greatly influence users' perception of space-making robots [6],[8],[9]. In HRI research, very few studies have been conducted to investigate robots that are not anthropomorphic, not mobile, and yet capable of reconfiguring the physical environment as do space-making robots [6].

B. Architectural Robotics

Architecture has long been conceptualized as "a machine for living in" [14] and, more recently, "a robot for living in" [15]. Green defines "architectural robotics" as "interactive, partly intelligent, and meticulously designed physical environments" [16]. Architectural Robotics is inspired by McCullough's vision of "a tangible information commons" in which a "richer, more enjoyable, more empowering, more ubiquitous media become much more difficult to separate from spatial experience" [17],[18]. Examples of architectural robotics include smart and mobile furnishings [19], reconfigurable work environments [3], and reconfigurable vehicle interiors [20]. Some of these are space-making robots [3],[20] and some of them are not [19]; some of these are intelligent and some are not. In any case, people may perceive intelligence in a robot that is without AI as human-agent interactions unfold [5],[10].

C. Shape Changing Interface

Space-making robots and shape-changing interfaces [21] are both characterized by their capacity to physically reconfigure. However, many shape-changing interfaces are designed specifically for communicating information to users (e.g., physical information displays) and offering dynamic affordances (e.g., shape-changing buttons) [22], whereas space-making robots shape the spatial envelope and, as a consequence, the human activities within it. Future work in shape-changing interfaces will reportedly expand, interestingly, to architectural applications [22],[23], user experiences [22],[24], and user perceptions [22], all of which would converge further this classification of interfaces and space-making robots. In this light, the investigation reported in this paper represents the frontier of shape-changing interface research by investigating users' perception of agency in an architectural, space-making interface.

III. USABILITY STUDY

To investigate the research question, a space-making robot prototype is employed that was previously developed by the authors [20],[25],[26]. This space-making robot is a tendon-actuated, continuum robot surface (Fig.1). The core of the robot surface is a 2-inch-thick foam panel banded by six thin, plywood collars (including two end-pieces) as armatures for 3D-printed guides through which three tendons are threaded, lengthwise. Motors mounted at the top of the surface wind the three tendons to reconfigure the surface into five different configurations as reported in [25]. The potential applications for this technology (e.g., reconfiguring spatial envelope and functionalities) are presented in our previous work [20],[26].

To eliminate usability issues, a qualitative pilot study was conducted with 12 university students (ages 18-32, 4 FM, 8 M) asked to perform a writing task with the robot surface and provide feedback (Fig.1). The study was IRB approved and participants signed a consent form for video and audio release. Participants identified the following usability issues: a more rigid surface is preferred for the work surface; the worksurface was not sufficiently stable for work activity; and participants wished for a more refined interaction and prototype. The prototype was modified accordingly, and the improved prototype was used for the experiments described.

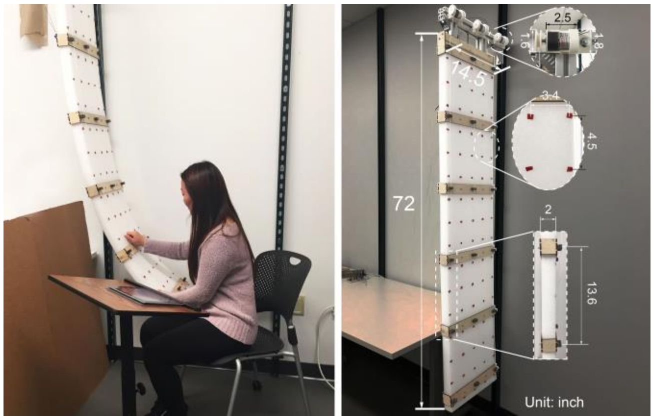

Figure 1. Robot surface (right) and photo from pilot study with user (left).

IV. IN-LAB EXPERIMENT

Our *hypothesis* is that users will perceive a space-making robot surface as an agent by the allocation of control, to the AI system or to the user. The *manipulated variable* here is "allocation of control" having two levels: the *automated* control simulated by WoZ [28] (treatment group); and the fully *user-controlled* surface movement (control group). For the treatment group, trajectories were designed that might trigger users' perception of robot agency [10] during a simple work task. Inspired by previous work in nonhumanoid robot movement design [8],[29], the authors designed and proposed the robot surface's "Dynamic Movement Protocol."

A. *Task and Possible Scenario*

In a room with only the wall-embedded robot surface and a chair (Fig. 2), a person is asked to copy a short paragraph on copy paper. This person might wish for a table or some other suitable writing surface, but there is none offered by the room; that is, until the embedded robotic surface provides one. While in motion, bending downward, the robotic surface pauses, permitting the user to recognize its hard surface as suited to the task. The user might consider this robot's affordance and may inspect it further. When the user moves closer, the robot surface adjusts its position subtly as a cue, and gently rests on the participant's lap to provide a writing surface. The user copies the paragraph easily; the robot surface then rises automatically, allowing the user to stand and leave the room.

B. *5-Step "Dynamic Movement Protocol"* (see video [27])

(1) When the user begins looking for a suitable worksurface, the wall-embedded robot surface, initially in an upright position, bends down automatically. (2) Then, the robotic surface pauses for 3 to 5 seconds after reaching an angled position at 15 degrees above the horizontal plane. This movement may elicit a user's attention and increase the robot's perceived "politeness" [8],[29]. (3) Subsequently, the robotic surface bends gently downward until it is horizontal—a prompt for user engagement [8],[29]. (4) When the user moves close enough and has her/his lap beneath the robot surface, the robot surface will subtly rest on her/his lap. This is the step where the robot fulfills it functionality [8]. (5) Finally, when the user finishes copying the paragraph and tries to stand up, the robot surface will automatically bend upwards to its initial, vertical, wall-embedded position.

C. *Experiment Design and Environment Setup*

The purpose of this experiment is to probe user perception and reaction to the autonomous (simulated by WoZ control) robot surface's behavior which traces our Dynamic Movement Protocol. Results can help us improve our movement protocol and experimental design, based on user feedback. The authors used Likert items to measure subconstructs of "agent" (based on prior literature) and then asked three open-ended questions probing the reasons behind user perception and reaction. Each trial was video recorded for further analysis. The experiment took about 20 minutes for participants, each compensated with a $7 USD gift card. The study was IRB approved and participants signed the consent form for video and audio release before the study.

Ten college students (ages 19-34, 7 FM, 3 M) and one mature adult (59, FM) participated in this between-group experiment with random assignment: 6 in the treatment group and 5 in the control group. As per the scenario, for the in-lab experiment, participants were asked to copy a short paragraph on copy paper in a room with the wall-embedded robot surface and a chair only (Fig.2). For the treatment group, Experimenter A (Fig.2), situated behind a one-way window, remotely controlled the robot surface behavior tracing the Dynamic Movement Protocol simulating autonomous robot movements for the participants (as per the Wizard of Oz technique [28]). For the control group, the remote controller was given to the participant to fully control the robot behavior. The trials were video recorded.

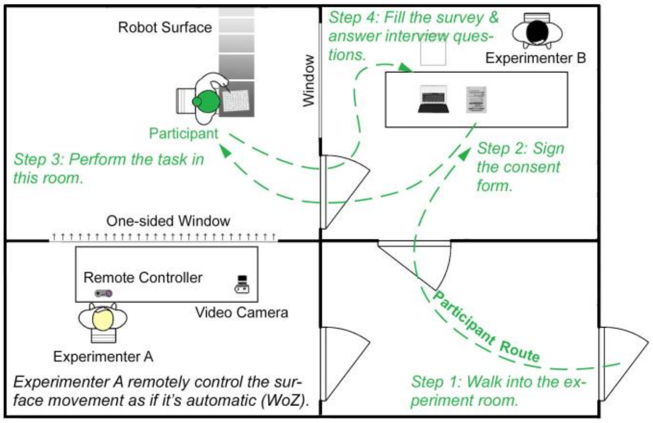

Figure 2. In-lab expeirment procedure diagram and environment setup.

After completing the task, participants were asked to answer the survey (Table 1). For participants in the treatment group only, a semi-structured interview was conducted by Experimenter B (Fig.2). The interview questions were: (1) *What did you think was happening when you saw the robot surface move?* (2) *Assuming the robot functioned properly, how did you interpret the robot surface's movement?* (3) *Do you consider the robot surface to be an intelligent agent, and why?*

D. *Survey Questions (Table I)*

Based on our definition of an "Agent" following the literature [8],[11],[13],[29], the authors measured people's perception of *intention* (Q5, Q9), *recognition* (Q4, Q7, Q14), and *intelligence* (Q2, Q6, Q8) of the robot surface. The authors also probed users' social perception [10],[11] of the robot surface by asking questions about *perceived cooperativeness* (Q11), *friendliness* (Q13), *welcome* (Q16), and *collaboration* (Q17) which were borrowed and modified from a validated "Social Perception" sub-scale [7],[30]. These 7-point Likert items were evaluated and iterated by three HRI experts for content and face validity several times. Here, the authors are by no means developing a validated scale for measuring "Agent Perception" (and there is not one yet), although the internal consistency of these 12 items were found to be very high (Cronbach alpha= 0.91). The authors ask questions directly about the subconstructs we aimed to measure [29].

TABLE I. SURVEY QUESTIONS FOR SUBCONSTRUCTS

Q2: The robotic surface seemed to think when doing something for you.
Q4: The robotic surface seemed to recognize that you needed a hard surface to write on.
Q5: The robotic surface didn't intend to do anything for you.
Q6: The robotic surface had no intelligence at all.
Q7: The robotic surface seemed to understand your needs.
Q8: The robotic surface was acting deliberately.
Q9: The robotic surface was trying to provide a work surface for you.
Q11: The robotic surface was trying to be cooperative.
Q13: The robotic surface was trying to be friendly.
Q14: The robotic surface didn't recognize what you needed to do.
Q16: The robotic surface was trying to be welcoming.
Q17: The robotic surface was collaborating with you.

E. Results and Findings for the In-lab Experiment

With only 5 and 6 participants respectively in the control and treatment groups (because of the pandemic, which closed our in-lab study prematurely), the survey results were limited. The findings presented below are mostly based on the interview results and video recorded observations.

Firstly, participants, irrespective of being assigned to the control or treatment groups, have very different reactions: 6 participants used the robot surface as the writing surface, 4 participants used interior walls or windows as writing surfaces, and 1 participant used his lap. This suggests that our Dynamic Movement Protocol could be improved to account for different user reactions; this improvement was made for the online experiment reported in the next section (see, also, [29],[32]).

Secondly, participants do perceive *intention*, *recognition*, or *intelligence* out of the WoZ controlled movement, although some of them did not use the robot surface for the writing task because it did not seem OK for writing. This may suggest that a user's failure to use the robot surface does not necessarily predict her/his positive perception of *intention*, *recognition*, or *intelligence*. For instance, more than one user offered that she/he understood "the robot surface was providing a table for me," but didn't use it because "the material looked soft."

Thirdly, participants who perceived *intention*, *recognition*, and *intelligence* of the robot surface may not attribute these characters to the robot, as they suspected *someone else* was controlling the system. One (student) participant was an HRI researcher who said, "that window might be a one-way mirror." Participants in this mindset may give low scores to most of the survey items, as this participant did.

Finally, in our interview, four out of the six participants perceived the robot surface as "accommodating," "providing a table," or "having done the right thing." In the survey responses from the 11 participants, there is an average of about 2 points higher for most of the 7-point Likert items from the treatment group than the control group. This may suggest that our experiment design in general works, and our Dynamic Movement Protocol fulfilled its purpose sufficiently to trigger user's agency perception.

V. ONLINE EXPERIMENT

To compensate for the lack of in-lab participants (given the closure of our lab due to the pandemic), an online, between-group study was conducted with 120 MTurk *Master Workers* "proven reliable" in previous studies, 60 assigned to each group: treatment and control (41 FM, 79 M; 65 workers 25-39; 52 workers 40-60; 2 workers over 60; 1 worker 18-24). Workers were paid a high market rate of 1.5 and 1.2 dollars respectively for participating in the 15-minute (treatment group) or 12-minute (control group), IRB approved study. Following prior HCI research ([29],[33]), our online studies asked participants to imagine themselves in the interactive experiment settings to then answer interpretive questions. With rigorous exclusion methods, participates can vividly transport themselves into the experiment settings and provide valid feedback of their perceptions, emotions, etc. [29],[33].

A. Survey Design

In the online surveys, a video narrative of the in-lab protocol (treatment group [27]; control group [32]) was played for participants who were asked to imagine participating in the in-lab experiment and to answer questions on how they would react, and why. Then, online participants were asked to answer survey questions as offered in Table I. Finally, for the treatment group only, the same three open-ended questions asked of the in-lab group were asked.

B. Results and Findings

The authors screened the data and excluded two observations in the control group because their responses for questions before the Likert items were not question-related. 118 observations remained left for analysis. Results are as follows: Q2, Q6, and Q8 have an acceptable internal consistency (Cronbach alpha= 0.79) measuring *perceived intelligence*; Q4, Q7, and Q14 also have an acceptable internal consistency (Cronbach alpha= 0.72) measuring *perceived recognition*; and Q5 and Q9 have a significant correlation (rs(58) = 0.61, p< 0.001) measuring *perceived intention*. Fig.3 presents the descriptive statistics for each subconstruct, calculated based on values from 1 (strongly disagree) to 7 (strongly agree). The coding for the each subconstruct in Fig.3 with the corresponding survey question number is: "Intel" for Perceived Intelligence (Q2, Q6, Q8), "Rec" Perceived Recognition (Q4, Q7, Q14), "Inten" for Perceived Intention (Q5, Q9), "Coop" for Perceived Cooperation (Q11), "Col" for Perceived Collaboration (Q17), "Fri" for Perceived Friendliness (Q13), and "Wel" for Perceived Welcome (Q16). Values for Q5, Q6, and Q14 are reversed before calculation.

The median values from the treatment group are all equal to or greater than 5 (somewhat agree); while values from the control group range from 2 (disagree) to 4 (neutral). The differences between *Md* (treatment group) *and Md* (control group) for these seven subconstructs range from 1.75 to 3.00. This suggests a general perception difference around "somewhat disagree" and "somewhat agree" for the participants in different groups. In addition, SD values in treatment group are all smaller than the ones for the control group, with the differences ranging from 0.18 to 0.51. This suggests that participants' opinions converge better in the treatment group than in control group.

A Kruskal-Wallis H test was performed to explore "perceived intelligence" (mean values of Q2, Q6, and Q8) as "group assignment of the participants" (treatment or control group). There is a statistically significant difference between the perceived intelligence and participant groups (χ 2 (1, N = 60) = 21.72, p< 0.001) with a mean rank of "perceived intelligence" of 4.69 for treatment group and 3.09 for control group (mean ranks presented in Fig.3). The authors did the same test for all other subconstructs, and the results are presented in Table II. The extremely small p-values suggest that participants in the treatment group did perceive more *intelligence, recognition, intention, cooperativeness, collaboration, friendliness,* and *welcome* from the robotic surface than the participants in the control group.

Answers from the three open-ended questions further explained the reason behind participants' responses. 43 of the 60 treatment participants (72%) considered the robot surface intelligent, and at least 38 of them said it was intelligent because it "recognized what I need," "understood where my lap was," or "sensed I was in the room," and then "formed a

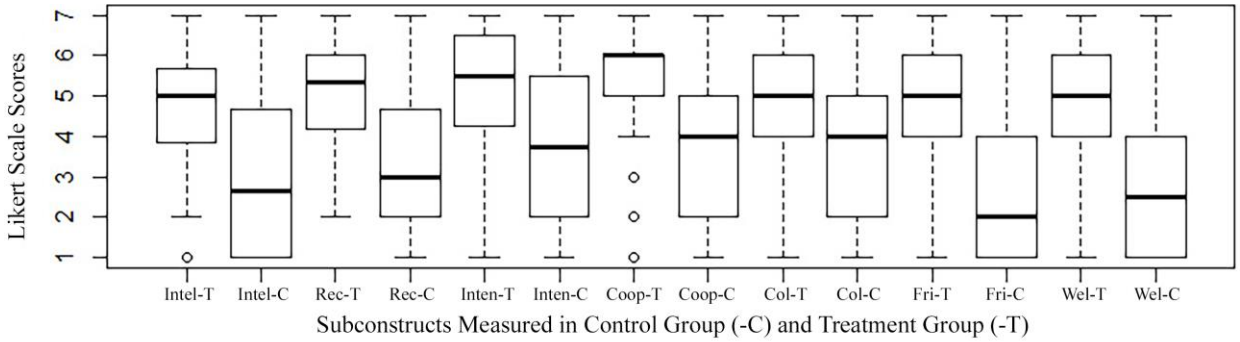

Figure 3. Online Experiment Results: Descriptive Statistics

desk," "adjusted itself per individual," "acted accordingly," etc. In other words, the reasons for perceiving the robot surface as intelligent is that *the robot surface recognized the situation and then performed an intentional and helpful act.* There are 15 participants who did not think it was intelligent: 6 of them did perceive its intention or recognition but argued "it was programmed to do so"; 4 of them said it was not intelligent because "an experimenter was controlling it"; 5 of them reported its actuation velocity didn't match their expectations. Finally, there are 2 participants not sure if it was intelligent as they suspected "it was controller by someone else."

TABLE II. KRUSKAL-WALLIS H TEST RESULTS

Subconstruct	**Kruskal-Wallis H Test Results**
Perceived Intelligence	$\chi 2$ (1, N = 60) = 21.72, p< 0.001
Perceived Recognition	$\chi 2$ (1, N = 60) = 36.70, p< 0.001
Perceived Intention	$\chi 2$ (1, N = 60) = 18.51, p< 0.001
Perceived Cooperativeness	$\chi 2$ (1, N = 60) = 21.29, p< 0.001
Perceived Collaboration	$\chi 2$ (1, N = 60) = 12.51, p< 0.001
Perceived Friendliness	$\chi 2$ (1, N = 60) = 20.79, p< 0.001
Perceived Welcome	$\chi 2$ (1, N = 60) = 20.16, p< 0.001

VI. DISCUSSION

Both our qualitative and quantitative results from the online experiment suggest that people do perceive *intention*, *recognition*, and *intelligence* in the robot surface, a space-making robot reconfiguring the space from "a room without worksurfaces" to "a room with a worksurface"—a change in room functionality. The authors would moreover argue that the "allocation of control" can be a key factor influencing users' perception of human-(space-making) robot interaction, as manipulating this variable in our online experiment was associated with users' perception of the seven subconstructs (*intention, recognition, intelligence, cooperativeness, collaboration, friendliness,* and *welcome*), all changed from negative (around "somewhat disagree") to positive (around "somewhat agree"). This change in perception can be attributed to multiple aspects of the WoZ control of robot's behavior, including its dynamics, speed, and trajectory: All aspects warrant further investigation.

Based on qualitative results from both in-lab and online studies, there is a strong internal consistency and an underlying narrative among users' perception of *intention*, *recognition*, and *intelligence*. Our statistical analysis shows that all items for these three subconstructs together had strong internal consistency (Cronbach alpha=0.89 for treatment group, and 0.92 for control group). The narrative beneath this correlation is as follows: *users believed that the robot surface recognized their situational needs and, in response, performed an intentional and helpful act. As such, participants considered the robot surface as intelligent.* This means that even though the space-making robot is not anthropomorphic, not animal-like, not mobile but, instead, embedded in the spatial envelope of the room, as long as the robot's behavior (i.e. movement) responds to a person's intentional stance [13], a person will likely perceive it as a "logical agent" [13] with intention, recognition, and intelligence.

Our quantitative results show that people did perceive the robot surface as trying to be *cooperative*, *collaborative*, *friendly*, and *welcoming* with a mean rank of 4.93. Although more empirical studies are needed to conclude that "space-making robots are social actors" [4], our study does suggest that the designed, WoZ controlled, and dynamic movement of a space-making robot can be perceived by people as social.

VII. LIMITATION

There are a number of limitation to our findings. Firstly, most of the experiment data, except for the video recordings from the in-lab experiment, were self-reported, which may pose validity problems. Secondly, the authors did not insert "attention checkers" within the online questionnaire. However, we did preselect reliable participants (*Master Workers* only), pay workers a higher market-rate reward, and use multiple screeners for the data as recommended by the literature for MTurk experiment validity [33]. Our online survey was conveniently short, taking only, on average, 600secs for the treatment group and 377secs for the control group (since the latter had three less open-ended questions). Thirdly, due to the pandemic, the authors were forced to move the in-lab experiment to an on-line platform. Although former studies found that MTurk workers "buy into interactive experiments and trust researchers as much as participants in lab studies" [33], it is still possible that "ecological validity" may have been sacrificed [29]. Finally, the 12 Likert items used in the two studies cannot be characterized as a validated scale. Although the authors tried their best to improve the validity of these items through literature backup and expert evaluations, it is not the focus in this paper to develop such a scale. Nevertheless, these 12 items did achieve high internal consistency and may serve as the raw material for researchers who want to develop a validated scale of "Perceived Agency" in the future.

VIII. CONCLUSIONS

Are space-making robots, agents? Based on the investigation reported here, the authors conclude that people do perceive *intention, recognition, intelligence, cooperativeness, collaboration, friendliness,* and *welcome* of a space-making robot. Following the literature cited here, these seven constructs encompassing the key aspects of what defines an "agent" (a logical agent and a social actor) served as a system of measurement for arriving at this conclusion—that space-making robots can be agents. However, more empirical studies are needed for a more affirmative conclusion. While space-making robots may become numerous in the built environment (e.g., interactive spaces, smart rooms, smart cities, etc.), the conclusions reported here are significant, moreover, for their broader implications for conceptualizing human-machine interactions and probing notions of intelligence.

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