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Sustainability in Community Building: Framing Design Thinking Using a Complex Adaptive Systems Perspective

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Abstract: Complex adaptive systems (CAS) theory is acquiring mainstream recognition in sustainable community building. In this paper, we bring the applicability of CAS theory into sharper focus, highlighting its potential for integrating complexity and adaptivity of community into a structured body of knowledge while also providing a thought pattern for generating, implementing and validating new design ideas. Therefore, this paper aims to propose a framework of design thinking that uses a CAS perspective to aid designers in conceiving new community building design ideas efficiently. Next, this paper presents the results of a cognitive design experiment where functional magnetic resonance imaging (fMRI) and extended protocol analysis methods were combined to examine the validities of the proposed design thinking framework in community building. The results show that the Agent-Interaction-Adaptation (AIA) design thinking framework has the ability to promote designers' extension of idea space, brain activation and idea quality in contrast to a traditional design thinking framework, but it did not significantly increase the designers' idea quantity.

Keywords: sustainability; community building; CAS theory; design thinking

1. Introduction

In the context of urban stock development, as the basic unit of urban society, sustainable community building is crucial to solving this problem [1]. However, the premise is to understand the extremely complicated relationships between community components in detail [2]. At the same time, with the updating of complex adaptive system (CAS) theory and comprehensive analysis strategy, the neo-rationality based on the CAS theory is rapidly forming a new paradigm [3], which can help us in understanding and modelling the multi-layered structure and emergence of sustainable communities [4].

CAS theory was proposed in 1994 by Professor John H. Holland (JH Holland), one of the founders of the Santa Fe Institute (SFI). The theory claims that the agents of the system have dynamic and changeable characteristics and the ability to interact with other agents, so as to adapt to the surrounding environment and continue to change its own system and composition, eventually evolving into a new system. Conceptually, CAS theory also involves ideas from systems thinking, such as feedback loops, with the understanding that these fields constitute similarly holistic methods of viewing problems [5]. Meanwhile, the community-level building is seen as a series of highly contextual, interaction-oriented, and iterative processes [6]; thus, CAS theory is not only an appropriate tool for community development policymakers but is also capable of providing insight for practitioners involved in community-level interventions [3]. In this paper, we assume that CAS theory can be applied as a thinking pattern to facilitate thinking in community building design or other system engineering designs. Our eventual objective is to propose a framework of design thinking that uses a CAS perspective to aid designers in conceiving new community building design ideas efficiently.

Design thinking theory and CAS theory both lend themselves to broad spectra of interpretation and definition [7,8]. Whereas design thinking is a different way to meet innovation challenges, it does not start with technology but tries to find a market for new technologies [9]. Design thinking starts with human motivation and needs; it gets inspiration from humans and considers humans first to seek breakthrough innovations [10]. As a thinking process, design thinking emphasizes the balance between visualization and abstraction, divergence and convergence, analysis and synthesis, logic and intuition [11]. In a word, design thinking is not art, nor science, nor religion, but the ability to integrate thinking.

In order to declare the applicability of CAS theory within design thinking for community building, this paper takes some of the original ideas from CAS theory and presents them, with examples, as equivalent concepts within design thinking. On this basis, a framework of design thinking—Agent-Interaction-Adaptation (AIA) is proposed to aid designers in sustainable community building; as design thinking is a fruitful fusion of analytical thinking and intuitive thinking [9], we combined functional magnetic resonance imaging (fMRI) and extended protocol analysis methods to examine the validities of using the AIA design thinking framework in this research.

2. Related Literature

To explore the framework of design thinking using a CAS perspective, this research primarily focuses on the literature of CAS theory in a community building and design thinking framework.

2.1. CAS Theory in Community Building

At present, the complexity of urban development is becoming increasingly diversified and complicated; recognizing and adapting to complexity has become one of the development directions in the field of urban planning and community building [12]. Prior studies have suggested that CAS theory has the ability to analyze the complexity and adaptivity in community building [13], and establish a new theoretical framework for the coexistence of continuity and discontinuity, certainty and uncertainty, predictability and unpredictability [14]. For instance, Olazabal [15] promoted the generation of new knowledge to achieve a sustainable transformation of community by understanding it as a CAS; Nel et al. [16] proposed a conceptual framework for understanding dynamic change of communities based on CAS theory; Wohl [17] constructed a multi-agent-based dynamic system model for community building by regarding community as a CAS with spatial characteristics; Neely [3] proposed the correlations between community building theory and CAS theory to call for understanding more thoroughly the contextualized nature of community building.

Taken together, the literature has supported an argument for the validity of community as a CAS, but little research has yet been carried out on the level of design thinking using a CAS perspective in community building. Thus, it is difficult to establish an effective design theory system for aiding designers in conceiving new community building design ideas. Meanwhile, design thinking also needs an accurate theoretical framework to consider the interactions among humans with nature, cyber and artificial systems [18]. Thus, we suggest a hypothesis that the AIA design thinking framework is effective in conceiving new community building design ideas. To propose the AIA framework, the background is required.

2.2. Background of the Proposed Framework

The urban planning process is central to the evolution of modern urban planning, and its steps are refined acutely as an eight-step process involving: (1) issue identification; (2) goal formulation; (3) data collection and analysis; (4) objective determination; (5) alternative consideration and plan evaluation; (6) plan selection; (7) plan implementation and (8) outcome monitoring. [19]. Thus, the urban planning process is actually a kind of design thinking process and can be explained by design thinking frameworks in the design research field. The design thinking framework is also a series of regular steps. For instance, a d. school team in Stanford University presented a five-stage design thinking framework: empathize, define, ideate, prototype and test; IDEO suggested that the stages of the design thinking implementation process can be described as discovery, interpretation, ideation, experimentation and evolution [7]; The Design Council of the UK [20] proposed the Double Diamond Model which includes four stages: discover, define, develop and deliver. However, there remains a gap between these frameworks and design tasks with complex systems such as community building.

Function-Behavior-Structure (FBS) is a framework used to elucidate systems design thinking; Kan & Gero [21] offered a definition of it, and Figure 1 shows the model.

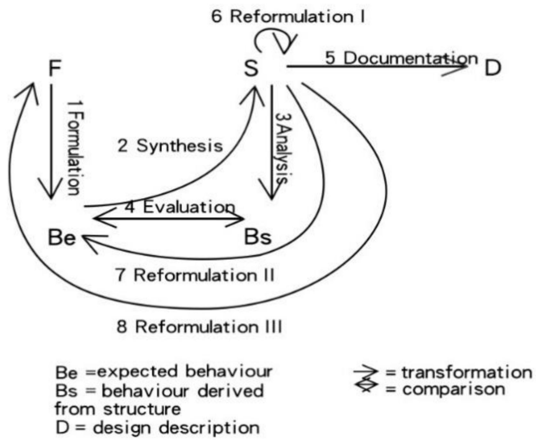

Figure 1. Model of Function-Behavior-Structure (FBS).

Kathehi et al. [22] offered another definition, stating that "FBS relates the components (structures) in a system to their purpose (function) in the system and the mechanisms that enable them to perform their functions (behavior)." Thus, many engineering students and software developers utilize the FBS framework [23]. The FBS framework is also expanded to the K-12 arena for understanding cognition within complex systems [20,24,25]. However, FBS is not a thorough theory for describing the design of systems, but rather a framework which helps understand human cognition in complex systems [26]. In contrast to CAS theory, FBS obviously ignores the hidden order in complex systems [27].

Herein, we aim to use a CAS perspective to propose the AIA design thinking framework to deal with the growing complexity in community building, which is not a series of regular steps, but a system with overlapping design thinking fields. These three overlapping fields in the AIA design thinking framework are Agent, Interaction and Adaptation. The reason why we call them design thinking fields rather than design thinking steps is that they are not carried out in sequence but repeated more than once in a process to improve the original ideas and explore new directions. Furthermore, we introduce the knowledge field theory into the AIA design thinking framework, which provides a theoretical mechanism of knowledge flow among these three design thinking fields.

3. AIA Design Thinking Framework

Definition of the AIA design thinking framework requires an understanding of CAS theory and possible relationships with design thinking. This section provides a description of three seminal CAS phenomena as equivalent concepts within design thinking to be considered in the AIA design thinking framework: Agent, Interaction and Adaptation.

3.1. Agent

The core idea of CAS theory is that "Adaptation builds complexity" [27]; Holland also regards the basic units of a system as "Adaptive Agents" which interact with each other and environments to drive the system's development and evolution. Thus, the idea of "Adaptive Agents" deconstructs the dualism based on the constructivism with separation of "entity" and "relationship", and proposes a new way of understanding the relationship between "entity" and "relationship" based on generativism.

In current design thinking frameworks, the design process can be divided into some stages [28–30], whereas using a CAS perspective, the design process is an indivisible system generated by the repetitive accumulation process of "Adaptive Agents". In community building, agents can be considered as humans, buildings, space, products, transportations and service.

3.2. Interaction

Cordier et al. [31] offered the definition of "interaction" which means the mutual action or effects which may exist between two or more objects and two or more phenomena; it is always followed by one or several influences. There are three patterns of interaction in a CAS: non-linearity, self-organization and emergence [32]; the three patterns are mutually dependent [33] and specific to design thinking. Non-linearity illuminates the connection between two agents, including rates of change, disorder, chaos and stability between them, positive and negative feedback loops. Self-organization increases the order between the agents' interaction and even generates a new order with the different agents behaving autonomously. Emergence contains radically new processes and agent interactions due to new and radical finding, concept generation, interpretation, experimentation and evolution in design thinking.

3.3. Adaptation

The adaptation of a CAS is reflected in the adaptive response to changes of the environment by adjusting its structure or parameters so that the system can make a correct and reasonable response to external contexts [34]. Think of adaptation in CAS theory as the implementation process that leads from the project stage into people's lives, and it may provide more dynamic feedback to the whole design process.

3.4. Proposed Framework: Model of the AIA

We use the ten design tools summarized by Liedtka [35] as a toolkit, and introduce the knowledge field theory as a theoretical mechanism of knowledge flow among design thinking fields to propose the model of the AIA design thinking framework, and Figure 2 shows the model.

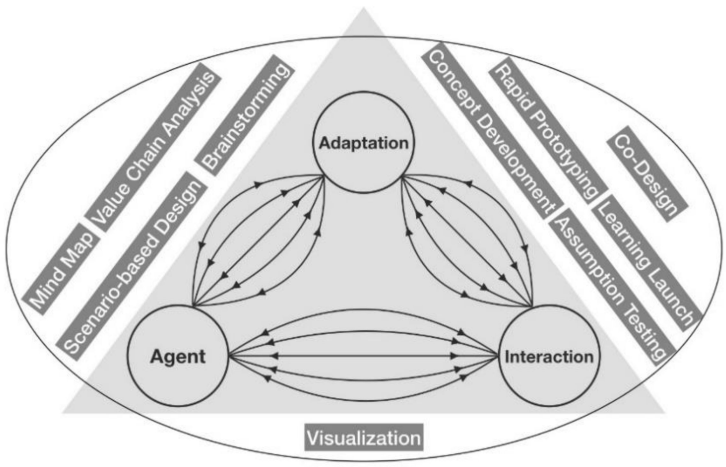

Figure 2. Model of the Agent-Interaction-Adaptation (AIA) design thinking framework.

Based on the knowledge field theory [36,37], we define the field source, field strength, field force, knowledge distance, knowledge stock, knowledge energy and knowledge flow in the AIA framework as follows.

3.4.1. Field Source in the AIA Framework

Field source is defined as the point where knowledge energy gathers, thus field source is the origin of knowledge field. In the AIA framework, the three field sources are "Agents", "Interaction" and "Adaptation". The knowledge energy of the field source is the highest; the farther away from the field source, the lower the knowledge energy. The knowledge energy K_T of the field source represents the total energy of the knowledge field. Due to the existence of tacit knowledge and integration effects, K_T is greater than the sum of linear superposition of each knowledge actor's energy. Assuming that the total number of knowledge actors in a knowledge field is n, then the knowledge energy of the field source is denoted as K_T:

$$K_T = f(K_1, K_2, K_3, \ldots, K_n) \tag{1}$$

With the evolution of the knowledge field, the state of field sources also changes. In the early stage of the formation, field sources are the three seminal CAS phenomena—"Agents", "Interaction" and "Adaptation". With the accumulation of knowledge resources in the three fields, the relations among knowledge actors continues to strengthen, the character and composition of the field source also become more and more complex. Thus, it is impossible to characterize all the information of the field sources simply by certain phenomena. At this time, the field source is not of a physical nature but reflected as an integration effect.

3.4.2. Field Source in the AIA Framework

Field strength is the strength of knowledge creation and demand for knowledge creation [38]. Field strength E represents the basic character of a knowledge field, which can be used to characterize the radiation ability and influence on the surrounding environment.

3.4.3. Field Force in the AIA Framework

Field force in the AIA framework refers to the effect of the three knowledge fields in absorbing and integrating related innovation resources, as well as the abilities of knowledge spillover and transformation between "explicit-tacit" knowledge. Thus, field force is a vector whose magnitude and direction are related to tie strength and the characters of related subjects.

3.4.4. Knowledge Distance in the AIA Framework

Knowledge distance [39] is the degree of difference in knowledge between individuals and is reflected in three aspects: difference in knowledge level r_1, the knowledge relevance r_2 (the stronger the knowledge relevance, the smaller the knowledge distance) and cultural difference r_3, knowledge distance, which is defined as:

$$R = f(r) = f(r_1, r_2, r_3) = \sqrt{(\mu_1 r_1)^2 + (\mu_2 r_2)^2 + (\mu_3 r_3)^2} \tag{2}$$

In the equation, μ_1, μ_2 and μ_3 respectively represent the weight of each aspect.

3.4.5. Knowledge Stock in the AIA framework

Knowledge stock is the total amount of knowledge resources owned by individuals at a specific point in time and reflected in three aspects: quantity of explicit knowledge q_1, quantity of tacit knowledge q_2 and knowledge quality q_3; the knowledge stock is defined as:

$$Q = f(q) = f(q_1, q_2, q_3) = \sqrt{(\delta_1 q_1)^2 + (\delta_2 q_2)^2 + (\delta_3 q_3)^2} \tag{3}$$

In the equation, δ_1, δ_2 and δ_3, respectively, represent the weight of each aspect.

3.4.6. Knowledge Energy in the AIA Framework

Knowledge energy K_i represents the knowledge level of an individual; it is positively correlated with own knowledge stock q_i, and negatively correlated with the knowledge distance r_i; L is the field boundary; the knowledge energy of individual i is denoted as:

$$K_i = -\int_i^L q_i \, E_i dr \tag{4}$$

As $Fi = \eta \frac{Q.q}{{r_i}^2}$ and $E = \frac{F}{q}$, field strength at individual i is denoted as:

$$E_i = \eta \frac{Q}{{r_i}^2} \tag{5}$$

Where η is the parameter to be estimated, put Equation (4) into Equation (3) to get the knowledge energy of individual i, which is:

$$K_i = -\int_i^L q_i \, E_i dr = -\eta \int_i^L \frac{q_i Q}{{r_i}^2} dr = \eta \frac{q_i Q}{r_i} \tag{6}$$

Formula (6) shows that the knowledge energy of an individual is not only related to own knowledge stock, but also to the field source's knowledge stock; it can be inferred that the integration effect has a positive effect on the improvement of an individual's innovation ability in the AIA framework.

3.4.7. Knowledge Flow in the AIA Framework

Knowledge flow in the AIA framework is the directional flow of knowledge, the quantity of knowledge flow I represents the strength of knowledge flow in knowledge fields, and directly reflects the active degree of knowledge transformation and sharing among individuals. The formula for knowledge flow is:

$$I_{i \to \mathrm{j}} = \frac{F_T}{r_{ij}} \tag{7}$$

In the equation, the direction of knowledge flow is from innovation individual i to j; r_{ij} represents the knowledge distance between innovation individual i and j. The larger the knowledge distance, the higher the resistance to knowledge flow. F_T is the occasional force in knowledge fields that promotes knowledge flow; the greater the force, the higher the strength of knowledge flow.

4. Materials and Methods

From a fundamental viewpoint, in order to examine the validities of the AIA design thinking framework, we need to observe designers' thinking processes using the AIA design thinking framework. Although extended protocol analysis has been proven as a valid method of understanding a designer's thinking process, it is a type of phenomenological analysis [40]. Thus, the inner states of a designer's mind are still inexplicit while designers are engaged in community building works.

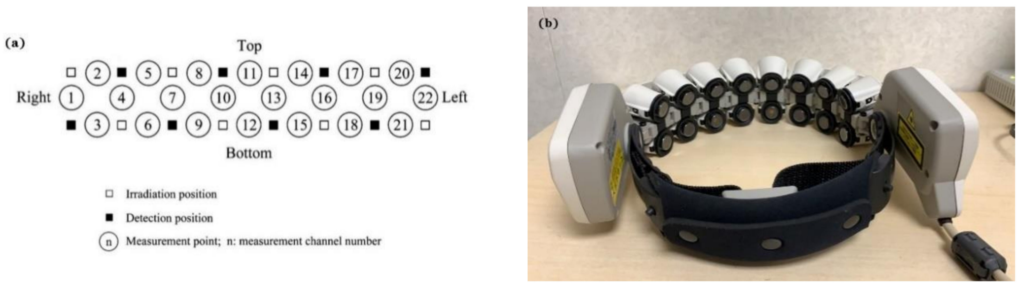

Figure 3. (**a**) Configuration of irradiation and detection positions and of measurement points in the WOT-220. (**b**) Photograph of the WOT-220.

Functional magnetic resonance imaging (fMRI) is a non-invasive technique for mapping the relative concentration changes in oxygenated and deoxygenated hemoglobin (oxy- and deoxy-Hb) in the human cerebral cortex, thus fMRI is considered as a powerful tool for evaluating brain activation [41]. In this research, we combine fMRI and extended protocol analysis methods to examine the validities of the AIA design thinking framework. Figure 3 shows the wearable optical topography headset (WOT-220) we used to get fMRI images which has a 2×8 alternating arrangement of irradiation and detection positions covering the entire forehead, with 22 measurement points as Figure 3a shows.

5. Experiment and Results

5.1. Participants

In this experiment, we invited 20 students pursuing master's degrees who were not experienced designers in the Japan Advanced Institute of Science and Technology (JAIST). The 20 participants in this experiment were all healthy adults (10 males and 10 females aged between 25 and 28 years, mean age of 26.1 ± 0.83 SD). All were right-handed and had no neurological abnormalities. Informed consent was obtained from each participant.

5.2. Outline of the Experiment

In this experiment, the 20 participants were divided into Group A and Group B, each group had 5 males and 5 females, they were all required to independently design new ideas for the JAIST-centred community for more sustainability within an hour. The difference was that Group A was trained to use the AIA design thinking framework in the design process, whereas Group B completed the design task using the traditional design thinking framework [42] with the same toolkit. During the design process, every participant was asked to wear the WOT-220 and "think aloud" with an electronic video recorder recording.

5.3. Data Collection and Analysis

To elucidate the validities of using the AIA design thinking framework in the design process, we analyzed not only the design ideas generated by the participants but also their performance in the design process both internally and externally. The data collection was conducted in three phases. In phase 1, we collected participants' utterances as the protocol data for designing [43]. In phase 2, we used the WOT-220 to map the relative concentration changes in oxy-Hb in the participants' cerebral cortices for evaluating their brain activation [41]. In phase 3, we measured the idea quality and quantity of each participant using the method proposed by Shah et al. [44].

5.3.1. Data Collection and Analysis of Phase 1

We extracted new nouns from the utterances recorded in the design process and interviews. Next, we measured the conceptual distance $(x_i\ , y_i)$ of the new nouns from 'community' and 'sustainability' based on WordNet [45]; the extension of idea space is defined as $\sum_{i=1}^{N} \frac{\sqrt{x_i^2+y_i^2}}{N}$ (where N = number of new nouns). Table 1 shows each participant's extension of idea space.

Table 1. Each participant's extension of idea space.

Group A	Extension of Idea Space	Group B	Extension of Idea Space
A1	0.75	B1	0.64
A2	0.68	B2	0.41
A3	0.77	B3	0.46
A4	0.56	B4	0.45
A5	0.68	B5	0.69
A6	0.53	B6	0.56
A7	0.88	B7	0.41
A8	0.76	B8	0.51
A9	0.55	B9	0.64
A10	0.74	B10	0.49

Then we analyzed these data using the independent samples *t*-test; the results are presented in Table 2.

Table 2. Results of independent samples *t*-test analysis.

Group	Extension of Idea Space $\bar{X}$	Extension of Idea Space SD	Sig
A	0.69	0.11	0.03
B	0.53	0.1	<0.05

The results are significant, so it can be inferred that the AIA design thinking framework has the ability to promote participants' extension of idea space.

5.3.2. Data Collection and Analysis of Phase 2

We used the modified Beer–Lambert law to calculate changes in the result of the concentration and the effective optical path length for oxy-Hb:

$$\Delta(C_{oxy}\, L) = \Delta C'_{oxy(\lambda 1,\lambda 2)} = \left[\, \varepsilon_{deoxy(\lambda 1)}\ \Delta A_{(\lambda 2)} - \varepsilon_{deoxy(\lambda,2)}\ \Delta A_{(\lambda 1)} \right] / E \tag{8}$$

where

$$E = \varepsilon_{deoxy(\lambda 1)}\ \varepsilon_{oxy(\lambda 2)} \varepsilon_{deoxy(\lambda 2)}\ \varepsilon_{oxy(\lambda 1)} \tag{9}$$

In the equation, the Hb signals ($\Delta C'_{oxy(\lambda 1,\lambda 2)}$) represent changes in the concentration (C_{oxy}) multiplied by the indefinite optical path length (L) in the activation region. ΔA, ε_{oxy} and ε_{deoxy} are the changes in optical density of the detected light, the extinction coefficient of oxy-Hb and the extinction coefficient of deoxy-Hb for two wavelengths ($\lambda 1$ and $\lambda 2$). L is identical for every wavelength and constant [46].

The Hb signals were statistically assessed during the first ten minutes in the experiment and collected from the significant channels—channels 5, 6, 7, 8, 9, 10, 13 and 15 [41]. Then we used the oxy-Hb signal ($\Delta C'_{oxy}$) to represent participants' brain activation. Figure 4 shows participant A1's time course of averaged oxy-Hb signal (obtained from channels 5, 6, 7, 8, 9, 10, 13 and 15) and the baseline to remove low-frequency fluctuations caused by laser drifts or biological metabolism.

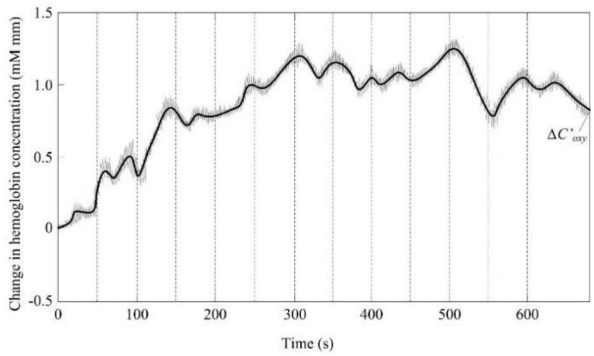

Figure 4. Participant A1's time course of averaged oxygenated hemoglobin (oxy-Hb) signal (obtained from channels 5, 6, 7, 8, 9, 10, 13 and 15) and the baseline.

Figure 5 shows the 20 participants' mean time courses of averaged $\Delta C'_{oxy}$ obtained from channels 5, 6, 7, 8, 9, 10, 13 and 15, which represent each participant's brain activation conditions related to the design task by using the AIA design thinking framework or the traditional design thinking framework.

We calculated the *t* value (independent samples *t*-test) between the mean changes in $\Delta C'_{oxy}$ in Group A and Group B to assess the group-related changes in $\Delta C'_{oxy}$ statistically. The *t* value (two-tailed *t*-test, $p < 0.01$) is significant, therefore, it can be inferred that the AIA design thinking framework has the ability to stimulate participants' brain activation more effectively in contrast with the traditional design thinking framework.

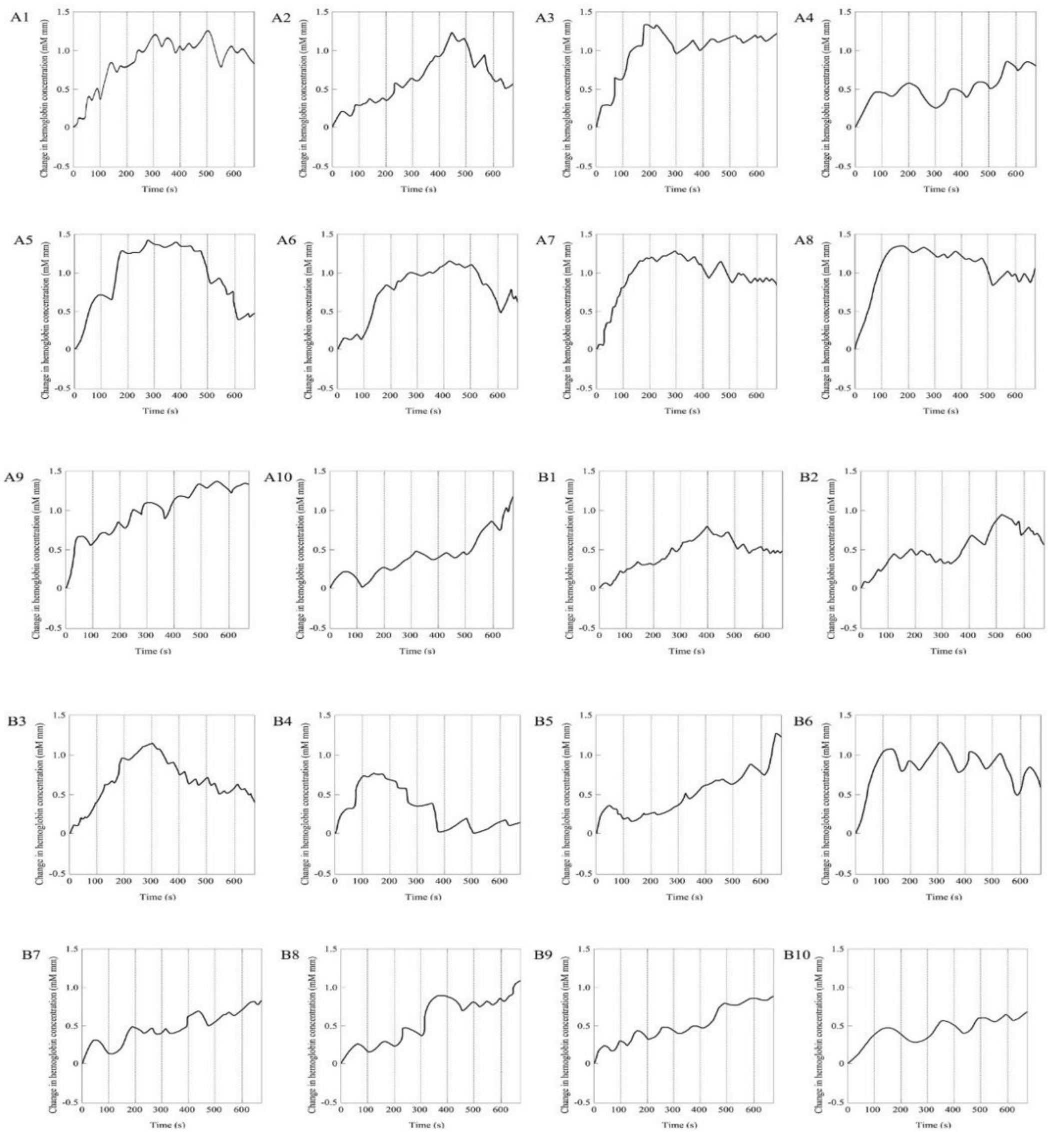

Figure 5. The 20 participants' mean time courses of averaged oxy-Hb signal ($\Delta C'_{oxy}$) obtained from channels 5, 6, 7, 8, 9, 10, 13 and 15.

5.3.3. Data Collection and Analysis of Phase 3

In this experiment, we adopted the method presented by Shah et al. [44] to measure each participant's idea quality and quantity. In this method, the idea quality could be estimated sufficiently well even if the quantitative information was not sufficient to perform a formal analysis in the concept stage. In addition, this method added all the quality scores for all the alternatives to achieve the total score for the set. As a result, the idea quality is denoted as:

$$M = \sum_{j=1}^{m} f_j \sum_{k=1}^{2} S_{jk} P_k / n * \sum_{j=1}^{m} f_j \tag{10}$$

In this equation, S_{jk} is the score for the quality of function j at stage k; m is the total number of functions; f_j is the weight of function j; p_k is the weight for stage k. The denominator is for normalizing to a scale of 10. The design ideas were collected from the 20 participants. Table 3 shows an evaluation of the quality and quantity of the 20 participants' ideas.

Table 3. Idea quality and quantity of each participant.

Group A	Idea Quality	Idea Quantity	Group B	Idea Quality	Idea Quantity
A1	6.75	2	B1	5.68	3
A2	5.72	3	B2	4.17	2
A3	4.49	2	B3	5.46	3
A4	6.74	1	B4	4.87	2
A5	4.03	3	B5	3.79	2
A6	5.36	2	B6	3.04	3
A7	3.58	3	B7	4.28	1
A8	6.98	2	B8	3.19	1
A9	4.21	2	B9	4.29	2
A10	6.47	3	B10	4.87	3

Then we analyzed these data using the independent samples *t*-test; the results are presented in Table 4.

Table 4. Results of independent samples *t*-test.

Group	Idea Quality $\bar{X}$	Idea Quality SD	Sig	Idea Quantity $\bar{X}$	Idea Quantity SD	Sig
A	5.43	1.28	0.043	2.3	0.67	0.76
B	4.36	0.88	<0.05	2.2	0.79	>0.05

The independent samples *t*-test analysis results of participants' idea quality are significant; it can be inferred that the AIA design thinking framework has the ability of promoting participants' idea quality, whereas the results of participants' idea quantity are not significant, so it is suggested that the AIA design thinking framework cannot increase participants' idea quantity.

6. Discussion

We primarily propose the AIA design thinking framework which includes three overlapping design thinking fields, and use the knowledge field theory as a theoretical mechanism of knowledge flow among design thinking fields. To examine the validities of the AIA design thinking framework, we conducted a controlled experiment for evaluating participants' extension of idea space, brain activation, idea quality and idea quantity.

6.1. Implications of the Experimental Results

This experiment revealed that that the AIA design thinking framework has the ability to promote a designer's extension of idea space, brain activation and idea quality in contrast with the traditional design thinking framework, but it did not significantly increase designers' idea quantity. We assume the following implications:

1. The AIA design thinking framework is better suited to dealing with complex and difficult design tasks, e.g., community building, as it significantly enhances a designer's deep thinking shown as the extension of idea space and idea quality.
2. The three overlapping design thinking fields in the AIA design thinking framework are repeated more than once to improve the original ideas and explore new directions as it significantly stimulates a designer's brain activation. Thus, the AIA design thinking framework is thought to be an effective method of facilitating iterative design.
3. The experiment required participants to design new ideas independently, which limits the knowledge flow to some extent and may be the reason why the AIA design thinking framework did not significantly increase the designers' idea quantity.

6.2. Practical, Theoretical and Political Implications

First, the AIA design thinking framework can be used in complex design tasks not only in community building, but also for more ill-defined design tasks, such as urban design and urban rural interaction. Similarly, Baoxing [47,48] proposed the new directions, methodology and features for urban governance and resilient urban design from the perspective of complex adaptive systems. In brief, the AIA design thinking framework starts from agents and adopts a bottom-up thinking strategy, hence, it can be considered as an agent-based thinking paradigm to solve the design task which needs multi-agent modelling and decentralized thinking.

Furthermore, the AIA design thinking framework can also be used as a kind of underlying logic, in conjunction with generative adversarial networks (GAN), which is a deep learning model and considered as one of the most promising methods for unsupervised learning on complex distributions—it should have great potential to create an artificial intelligence for aiding designers in conceiving design opportunities.

Finally, with the development of cities, urban design and community building are both facing highly complex and increasing uncertainties. Some uncertainties we can choose to tolerate, but for dealing with some uncertainties we have to design new forms of resilience, such as for dealing with COVID-19. The AIA design thinking framework can help policymakers understand and adapt to these uncertainties, as it utilizes CAS theory which holds the key idea that each agent in the system responds adaptively to external interference, and various heterogeneous adaptive agents have complex interactions with each other to create the evolutionary path and uncertainties of the system.

7. Conclusions and Future Tasks

This research contributes to both inventive practices and design thinking theories. The sustainability in community building motivates us to seek a novel design thinking framework using a complex adaptive systems perspective for such complex design tasks; to pursue breakthroughs, we point out the seminal CAS phenomena as equivalent concepts within design thinking and introduce the knowledge field theory as a theoretical mechanism of knowledge flow to propose the AIA design thinking framework. Then a controlled experiment was conducted to examine the validities of the AIA design thinking framework. The results show that the AIA design thinking framework has the ability to promote a designer's extension of idea space, brain activation and idea quality in contrast with the traditional design thinking framework. In addition, it was suggested that the AIA design thinking framework is effective in enhancing a designer's deep thinking and iterative design.

This research has limitations. For example, the participants were all required to independently design new ideas; thus, we focused on the role of the AIA design thinking framework in individual designers. As a result, we may have neglected the effect of the AIA design thinking framework on co-design or other forms of collaborative design. In addition, we analyzed participants' extension of idea space, brain activation, idea quality and idea quantity separately. For co-occurrences, utilizing specific structures for integrated analysis of these data can be considered for further study to explore additional insights into the AIA design thinking framework.

This research can move forward in a few directions for future research. First, we plan to apply the AIA design thinking framework in real sustainable community building projects, such as the NICE2035 Living Line project and DESIGN Harvests. Second, the effect of the AIA design thinking framework on collaborative design can be explored to deepen understanding of the AIA design thinking framework. Furthermore, we hope that systematic design thinking to aid designers in dealing with design tasks with plenty of complex dynamic interrelationships can be developed in future research by incorporating the AIA design thinking framework with artificial intelligence.

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