LeMo: Exploring Virtual Space for Collaborative Creativity

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ABSTRACT
Shared Virtual Environments (SVEs) have been extensively researched for education, entertainment, work, and training, yet there has been limited research on the creative aspects of collaboration in SVEs. This raises questions about how to design virtual working spaces to support collaborative creativity in SVEs. In this paper, we outline an SVE named LeMo, which allows two people to create music collaboratively. Then we present a study of LeMo, in which 42 users composed music together using three different virtual working space configurations. Results indicate that (i) two types of territory and working configurations emerged during collaborative composing (ii) when made available to them, personal working spaces were extensively used, and were considered to be essential to successful collaborative music making and (iii) a publicly visible personal working space was preferable to a publicly invisible one. Based on these findings, three corresponding design implications for Shared Virtual Environments focusing on supporting collaborative creativity are given.

Author Keywords
Collaborative creativity; Virtual Reality; Shared Virtual Environment; Collaborative Music Making; Sonic Interaction Design; Gesture design.

CCS Concepts
•Human-centered computing → Virtual reality; Collaborative interaction; Empirical studies in interaction design; Collaborative content creation;

INTRODUCTION
The real world provides us with a shared, all-encompassing space, in which we perceive rich information about the events and objects that can be manipulated and explored. Whilst non-immersive media have very different properties to real-world interaction [14], immersive media such as Virtual Reality (VR) offers people the ability to interact with others and objects in a way much more similar to the real world. Indeed, whilst many screen-based collaborative systems view users as people on the outside looking in [4], VR offers an opportunity to immerse people into the collaboration. Compared to traditional media, VR may provide a novel space for multisensory experience [37], a greater sense of community and more intuitive interactions [39], and may offer opportunities for new forms of human-to-computer interaction [21] and human-to-human interaction.

Following extensive studies on individual creativity, research attentions have shifted to the importance of collaboration in creativity [19, 38]. Whilst the potential of multi-user immersive virtual reality to facilitate social activities, learning and entertainment is well established [2, 23, 29], there is little research in the field of VR supporting collaborative creativity. As a result, there are many open research questions on how to design VR user experiences to support collaborative creativity. As a starting point, understanding the work space is crucial, as it is the fundamental resource which allows activities to happen [27]. Territoriality that emerges whilst performing activities, acts as a spatial strategy to affect, influence or control resources and access (cf. [30]), and plays an important role in managing interaction and resources [32]. In this paper we report on a study to explore the role of territoriality in VR by observing how participants use virtual working space and examining the emergence of territoriality during the usage, looking specifically on how different design of working space may affect participants' behavior.

We begin by reviewing related work in Social Virtual Environments (SVEs), space and territory in collaboration. Then we introduced our study, take Collaborative Music Making systems (CMMs) as an exemplar domain and review work in that area, detail the design of our VR system for collaboration. Finally the results are presented and discussed, design implications are given, and conclusions are made.

RELATED WORK

Shared Virtual Environments
Shared Virtual Environments (SVEs) are the result of a convergence of research interests in VR and Computer-Supported Cooperative Work (CSCW) [5]. Several terms are used to refer to collaborative uses of VR including Shared Virtual Environments (SVEs), Collaborative Virtual Environments (CVEs) and Social Virtual Reality [34, 42]. In this paper, we use the term SVEs to refer to all the collaborative environments that involve VR technology. As an extension of single-person Virtual Environments (VEs), SVEs typically emphasize the collaboration between users as opposed to a focus on rich simulation [22]. SVEs enable multiple people to communicate and interact with each other, provide a natural medium for three-dimensional CSCW [6], and are considered emerging

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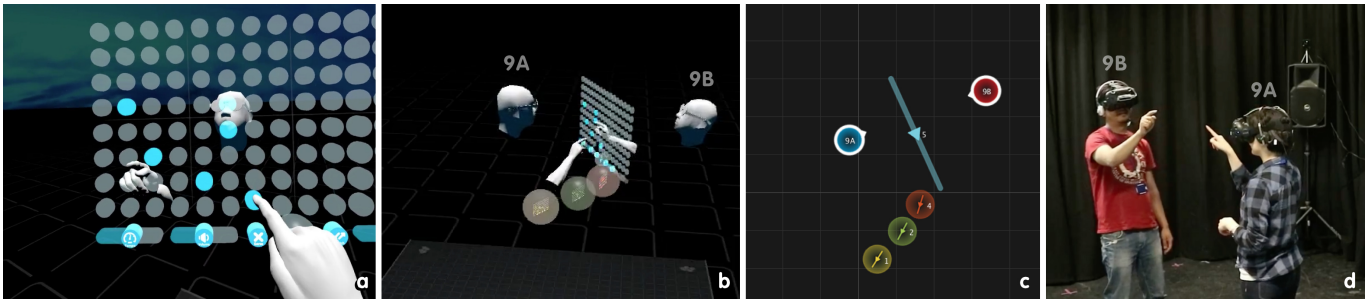

Figure 1. Participant 9A and participant 9B (Group 9) are editing notes on the same music interface. First person perspective of 9A (a); third person perspective (b); top view of arrangement plot generated by a reanimation system (c); real-world experience scene (d).

tools in supporting community activities [18]. Applications of SVEs range from online education [29], distributed work and training [23], to entertainment [24, 26].

Space and Territory in Collaboration

Space

The term "space" is used in many contexts (e.g. psychology), here, we only review the physical space. Space is a material, an invention, a construction that permits people to act [27]. It is the boundless three-dimensional extent in which objects and events have relative position and direction, and can be seen as a material given prior to the happening of actions. In this paper, we use the term "personal space" to refer to a specific working space assigned to a specific person, and "group space/shared space" to refer to a specific space assigned to a specific group prior to the start of activities. Similar to assigning physical space in reality, we can assign virtual 3D space to specific user(s) for performing activities in SVEs.

Territory

Territory emerges as a result of these actions happened in a space, it is thus the "production of actors" [27]. Human territoriality is a powerful and pervasive element in human being's lives [30]. Taylor argues that it is an *"interlocking system of attitudes, sentiments, and behaviors that are specific to a particular, usually delimited, site or location"*, which reflect and reinforce, for individuals or a small group *"some degree of excludability of use, responsibility for, and control over activities in these specific sites"* [36]. Similarly, Sack sees it as a basis of power, a spatial strategy to affect, influence, or control resources and people [30]. By claiming a space, territory helps people mediate their social interaction [1], which is a key element to collaboration [17]. As there is little research on territory in VR, instead, we review territory in table-top collaboration, in which territory plays an important role in collaboration. Collaborators use different types of territory to serve different needs, including sharing, exchanging or storing working tools and resources [32], although some research notes that removing territorial constraints can promote exploratory group activity [41]. Two main types of territory are identified from research on screen and tabletop mediated collaboration:

(1) *Personal territory* for performing independent activities. When provided with a personal territory, users prefer to test their contribution before introducing it to the group work [13]. This type of territory serves as a safe place to try and develop alternate ideas before publishing the ideas [35]. Users have been found to prefer to rotate items toward themselves in personal territory [35] and perform very few actions in their collaborators' personal territories [32].

(2) *Group territory* for performing the main task. In group territory, people create and develop new solutions, transfer resources and provide help [32]. It is interesting to note that the orientation properties of objects in the group territory can be used to convey support, to separate ideas or to group products [35].

In terms of designing for territoriality, Scott, Carpendale & Inkpen [32] suggested four guidelines for designing digital tabletop workspace: i) visibility of action; ii) an appropriate size of workspace; iii) providing functionality in the appropriate locality; iv) allowing grouping items to facilitate storage. Furthermore, visibility and transparency of action have been found to be important in designing group workspace, as they help collaborators to monitor each other's actions, maintaining workspace awareness during collaboration [25, 13]. However, this can result in cognitive overload, which some people found difficult to handle [13]. To date, little research has explored how such features of territoriality might be designed for and used in SVEs.

EXPERIMENT

Studies have shown that different types of territory exist and serve different functions in table-top collaboration [32, 41]. In this paper, we explore the territory and territorial behavior emerged in a VR setting. In creative group-work, enabling people to shift between individual creativity and tightly coupled collaboration is needed [12, 16], so that the collaborators can develop their own ideas without affecting others. Studies have also shown that adding personal workspace is helpful for collaboration, and visibility of co-workers' workspace is preferred but has no notable positive effect on the uses of personal workspace and may even have some negative effects [13]. In this paper we explore whether these findings apply to group and personal workspace in a VR setting, and whether the addition of personal workspace affects the emergence of territory and participants' collaboration strategies. Thus, we developed three hypotheses in keeping with research on collaboration in non-immersive media such as tabletops:

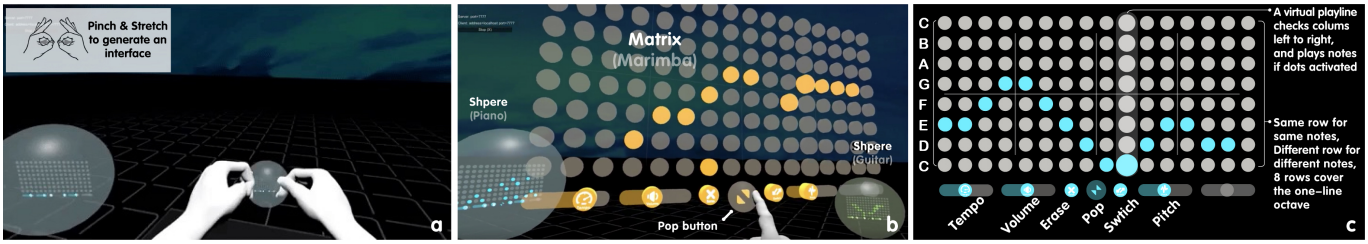

Figure 2. Gesture to generate a new interface (a); *Matrix* (opened interface) and *sphere* (packed interface), double tap the pop button to switch in between (b); An example layout of the interface when extended, currently the activated blue dots are EEFG GFED CCDE EDD or 3345 5432 1123 322, demonstrating the well-known melody of Ode to Joy by Beethoven (c).

H1 Different types of territories (personal/group territory) will emerge during collaboration in VR, and people's interactive behavior will change according to their location, cf. [32, 41].

H2 Providing personal spaces will facilitate efficient collaboration in VR, cf. [13].

H3 Publicly visible personal space will be preferred, comparing to publicly invisible personal space, cf. [13].

Creativity domain: collaborative music making

Music making has long been a key form of creativity. It is also a collaborative activity which relies on shared goals and understandings, and good interpersonal communication, making it an excellent activity through which to study collaborative activity. In 2003, Blaine-and Fels [7] explored the design criteria of collaborative music-making (CMM) systems, pointing out key features including the media used, player interaction, the systems' learning curves, physical interfaces and so on. The Networked Music Systems Classification Space was developed by Barbosa with inspiration from Rodden's Classification Space for groupware [3, 28], classifying these CMMs in terms of the time dimension (synchronous/asynchronous) and space dimension (remote/co-located). For example, Daisyphone [9], which provides shared editing of short musical loops falls into the remote synchronous network music systems in Barbosa's Classification Space. Other examples include reacTable [41] and BilliArT [8], both of which provide co-located shared musical experiences with tangible interfaces, and Ocarina [40], which provides a distributed music-making experience. However, it should be noted that despite decades of research into CMMs and SVEs, there have been relatively few SVEs which support CMM.

LeMo - A Virtual Reality Step Sequencer

To explore the use of spaces in collaboration in VR, and to fill the gap between CMMs and SVEs, we built Let's Move (LeMo)[1]. LeMo enables two users to manipulate virtual music interfaces together in an SVE to create a 16-beat music loop. LeMo was programmed in Unity, models and textures were made in Cinema 4D and Photoshop respectively. The run-time environment includes two HTC Vive headsets (each with Leap Motion mounted, see Figure 1d) and two PCs connected and synchronized via a LAN cable.

[1]Full source available at: https://sites.google.com/view/liangmen/projects/LeMo

LeMo presented in this paper is an extensively modified version of an earlier version [20]. Hereafter, "LeMo" specifically refers to this second version. LeMo has three key elements:

(1) Music interface. LeMo allows users to generate, remove, position and edit virtual music interfaces, which have two modes: *sphere* and *matrix* (Figure 2). Users can generate up to 8 *sphere*s with pinch and stretch gesture, see Figure 2a. Both the *sphere* and the *matrix* can be switched in between, repositioned or removed by manipulating the *sphere* or the pop button of the matrix with corresponding gestures. The *matrix* interface contains a grid of 16 x 8 dots, with controllers at the bottom. Each row represents the same pitch, forming an octave from bottom to top. Users can edit notes by tapping the dots. A vertical play-line repeatedly moves from left to right playing corresponding notes. In this way, each interface generates a 16-notes music loop. Three controllers (tempo, volume and pitch) and two functional buttons (erase and switch) are located at the bottom of the *matrix* interface.

(2) Avatars. Each user has an avatar, including a head and both hands (Figure 1). Avatars are synchronized with users' real movements in real time, including position and rotation of head, and gestures. LeMo provides visual aids for collaboration by synchronizing the virtual environment (virtual space and music interfaces) and avatars across a network, providing participants the sense of being in the same virtual world and manipulating the same set of music interfaces.

(3) A virtual space that includes a gray stage with a grid pattern (Figure 1a, b). Three types of stage setting were designed for this study and will be detailed later.

Besides these three fundamental elements, LeMo also has: spatialized audio so that users can hear where the sounds come from and the volume drops with distance; A data-log system to log user's interaction (e.g. users' heads' position and rotation, musical edits); A voice notification system to facilitate the experiment, e.g. in experimental scenario users will hear "1 minute left" and "end of session" notifications.

Independent variable

The spatial configuration is the independent variable in this experiment. To investigate the hypotheses we designed three space configurations as the independent variable levels, as shown in Figure 3, these include:

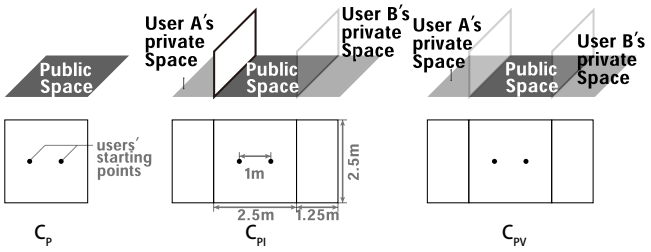

Figure 3. Three settings of spaces of the experiment, directional view(upper), top view (bottom).

Condition 1 - **P**ublic space only (referred to as C_P): where players can generate, remove or manipulate Spheres, and have equal access to all of the space and the music interfaces.

Condition 2 - **P**ublic space + Publicly **I**nvisible personal spaces (referred to as C_{PI}): in addition to the public space (in C_P), each user is also provided with a personal workspace that can only be accessed, heard and seen by the owner. Note when being inside personal spaces, users can still hear and see what's happening in the public space. Figure 3 (middle) shows the setting from user B's view.

Condition 3 - **P**ublic space + Publicly **V**isible personal spaces (referred to as C_{PV}): in addition to the public space (in C_P), each user is also provided with a personal workspace that is visible to their coworkers.

Dependent variables

To identify how users use the space and the effect of personal spaces, series of dependent variables were developed, split into *Participant Reports* and *Activity Assessment*.

Participants Reports

We developed questionnaires to identify participants' subjective assessments of the conditions and the collaboration experience. The Igroup Presence Questionnaire (IPQ) [31] was used to inform the design of questions about the sense of presence. Questions about output quality, communication, and contribution were adapted from the Mutual Engagement Questionnaire (MEQ) [10]. The rest of the questions were designed to question people's preference for conditions. The questionnaires included questions on:

(1) Presence: i) Sense of self-presence, ii) sense of co-worker's presence and iii) sense of collaborator's activities.

(2) Communication: quality of communication, which may vary as the visibility of spaces can possibly affect the embodiment and nonverbal communication.

(3) Content assessment: the satisfaction of the final music created reflects the quality of collaboration, cf. [10, 11].

(4) Preference: preference for the conditions, to see if users have subjective preferences towards the settings.

(5) Contribution: i) the feeling of self's contribution; ii) the feeling of others' contribution, to examine the effects of space setting on the sense of contribution.

These measures were grouped into a Post-Session Questionnaire (PSQ), see Table 1, to be filled after participants experiencing each condition, and a Comparison Questionnaire (CQ, see Table 2), to be filled at the end of the experiment.

Activity Assessments

Based on the data of users' head and hand movements and interactions, we developed the following measures of activity in the collaboration:

(1) Time and amount of use: i) number of uses of, ii) length of time of using, and iii) average duration of each use of personal space.

(2) Location and territory: i) distribution of participants' locations and interactions; ii) the sizes of personal/group territory if they emerge; iii) average distance between participants (cf. colocation in [10]).

(3) Attention: i) time participants spent paying attention to each other; ii) number of times of participants paid attention to each other.

(4) Contribution: i) number of music interface additions; ii) number of musical note edits.

Participants

Students at the authors' university were recruited through group emails. Each participant was compensated 10 GBP for their time. Twenty-one pairs of participants took part (25 males, 17 females; aged from 22 to 42, $M = 29$, $SD = 4.2$; 11.9% had no VR experience before, 16.7% tried VR once, 59.5% played 2-5 times and the rest 11.0% played more than 5 times or frequently). Half (21 participants) played a musical instrument and the average experience of composing collaboratively is 2.6 in a 10-point Likert scale (1 for no experience and 10 for highly extensive experience). Slightly more than half (52.4%) knew their experiment partner very well prior to the study, a third rated (33.3%) their partner as a stranger, the rest (14.3%) met their partner before but not know well.

Procedure

After reading the information form and signing the consent form, each pair of participants first received an explanation of the music interface of LeMo (see Figure 2c). Then one experimenter demonstrated all the interaction gestures supported in LeMo. By linking the demonstration with the first-person view shown on monitors, participants had a chance to learn how to play LeMo. Then participants took a trial (5-15 minutes) for trying all the ways of interaction. The trial ended once they were confident enough of LeMo. The length of time of the tutorial session was flexible to ensure participants with diverse musical knowledge could grasp LeMo. Participants were then asked to have three sessions of collaborative composing music that was mutually satisfying in the same room, each lasting 8 minutes based on our pilot study and a previous study [8], we found 8 minutes were sufficient for the task). Voice communication is crucial to simulate a real-world collaboration scenario and to a proper level of immersion, as currently LeMo does not support voice communication, we chose side-by-side collaboration in the same room to enable direct voice communication. To avoid the impact of adding personal spaces and

Table 1. Post-session questionnaire (PSQ)

Question	Measure
1-In the virtual world, I had a sense of "being there"	Sense of self-presence
2-My collaborator was there, collaborating with me together, all the time	Sense of other's presence
3-How satisfied are you with the final piece of music created in this session	Content assessments
4-How would you rate the quality of communication during the session	Communication quality
5-I had a clear sense of what my collaborator was doing	Sense of other's activity
6-The addition of personal spaces is very helpful to the task (only asked when personal space made available)	Preference of the sessions
7-The amount of your contribution to the joint piece of music	Amount of contribution
8-The amount of your collaborator's contribution to the joint piece of music	Amount of contribution
9-The quality of your contribution to the joint piece	Quality of contribution
10-The quality of your collaborator's contribution to the joint piece	Quality of Contribution

have a pure observation on how participants form their own proximity in the public space, all pairs started with C_P, and then C_{PI} and C_{PV} in a randomized sequence. We understand the exclusion of C_P from the randomization would lead to an insufficiently counterbalanced learning effect, which would affect H2, however, this also enabled us to fully avoid the learning effects of introducing personal space, providing a purer observation for H1. Moreover, the learning effect was well counterbalanced for H3 as the sequence of C_{PI} and C_{PV} were still fully randomized. Each session ended with the Post-Session Questionnaire (PSQ, see Table 1). The Comparison Questionnaire (CQ, see Table 2) and a short interview were carried out at the end of the experiment.

RESULTS

Participant reports

In this section we report on the results of the questionnaires. We found no significant differences in the results of the Post-Session Questionnaire and several significant differences in the Comparison Questionnaire. Binomial tests were run to see if the number of ratings for each option was significantly different than would be expected by chance, upper-tailed, lower-tailed or two-tailed tests were used accordingly. Next, results will be reported following the sub-type of measures.

Presence

(1) Self-presence. In all conditions, participants reported a high level of sense of self-presence (all $M > 8$ in a 10-point Likert Scale), indicating a proper level of immersion, which forms a solid base for this VR study. (2) Sense of collaborator's presence. Participants gave high ratings on sense of collaborator's presence in all conditions (all $M > 7.95$), although in the results of Comparison Questionnaire, a significant number (20 out of 42) of participants reported in C_{PI} they had the least strong sense of their collaborators' presence,

Table 2. Results of Binomial Test of the Comparison Questionnaire (CQ); lower-tailed test when $k < 14$, two-tailed test when $k = 14$, upper-tailed test when $k > 14$.

Question description	Option	C_P		C_{PI}		C_{PV}	
		k	p	k	p	k	p
CQ1-In which session, you made the music you were most satisfied with							
	most satisfied	8	0.0317	16	0.307	18	0.127
	second most satisfied	12	0.317	14	1.00	16	0.307
	least satisfied	22	0.00835	12	0.317	8	0.0317
CQ2-Which session you found most difficult to track collaborator's activities							
	hardest	14	1.00	19	0.0726	9	0.0667
	second hardest	8	0.0317	16	0.307	18	0.127
	least hardest	20	0.0384	7	0.0132	15	0.428
CQ3-Which session did you have the strongest sense that your collaborator was there working with you together							
	strongest	18	0.127	11	0.209	13	0.442
	second strongest	11	0.209	11	0.209	20	0.0384
	least strongest	13	0.442	20	0.0384	9	0.0667
CQ4-Which session did you have the best quality of communication							
	best	13	0.442	13	0.442	16	0.307
	second best	10	0.125	17	0.205	15	0.428
	least best	19	0.0726	12	0.317	11	0.209
CQ5-Which session had the best setting for creating music collaboratively							
	best	10	0.125	11	0.209	21	0.0187
	second best	16	0.307	13	0.442	13	0.442
	least best	16	0.307	18	0.307	8	0.0317
CQ6-Which session did you find most difficult to cooperate with collaborator							
	most difficult	15	0.428	17	0.205	10	0.125
	2nd most difficult	13	0.442	16	0.307	13	0.442
	least difficult	14	1.00	9	0.0667	19	0.0726
CQ7-Wich session do you feel you made the most contribution							
	the most	7	0.0132	13	0.442	22	0.00835
	second most	12	0.317	18	0.127	12	0.317
	least	22	0.00835	11	0.209	9	0.0667
CQ8-Which session do you feel your collaborator made the most contribution							
	the most	11	0.209	16	0.307	15	0.428
	second most	14	1.00	15	0.428	13	0.442
	least	17	0.205	11	0.209	14	1.00

Table 3. Results of Open-Ended Questions

Participant No. - Transcription (grouped according to 3 themes)
Advantages of providing personal spaces:
1A - [I could] try the effect of different settings without interrupting my collaborator.
2A - Had private space to test ideas in [C_{PI} and C_{PV}].
5A - [C_P] is good for people to work together, but without private space, I feel difficult to create my own idea.
6A - The [personal space] is nice to have. We prepared private rhythms and melodies and then showed them to each other.
9B - [Having] own space ... allowed us to compile our own piece of music in comparison to joint and single space in session 1. This enabled us to work on our separate compilation and merge to create the final piece, which was good!
14B - Very good to focus on one thing before sharing.
15A - I like doing something together but I also need my own work space.
Disadvantages of providing personal spaces:
1B - For me it was same since I did not use the private space.
Preference on publicly visible/invisible personal space:
3A - I was able to see my collaborator in ... session C_{PV}.
5A - [C_{PI}] was too private, I cannot see my partner's job. It feels not comfor-, table, [C_{PV}] was fine... it provides both privacy and teamwork equally.
5B - I feel more communicated with my collaborator during [C_P] and [C_{PV}].
7A - Session 3 and [C_{PV}] is the most helpful one.
8B - We can see what my collaborator is doing [in C_{PV}].
9A - [C_{PV} is] very distracting and prefer audio communication only.
10A - The way we can see each other but not hear from each other [C_{PV}] is most efficient.
17A - In [C_{PI}] we definitely felt more isolated from each other, but I am kind of used to this ... on in isolation.
18A - [C_{PI}] provides good private and public space, which allows us to work individually or cooperatively... In [C_{PI}], I had the weakest sense of communication because of the private space being opaque.
19B - [C_{PI}] help[ed] me to think on my own, without too much disturbance...

Table 4. Results of activity assessments and results of Wilcoxon Rank Sum Test (two-tailed)

Measure	Unit	C_P		C_{PI}		C_{PV}		C_P *vs* C_{PI}		C_P *vs* C_{PV}		C_{PI} *vs* C_{PV}	
		M	*SD*	*M*	*SD*	*M*	*SD*	*p*	*W*	*p*	*W*	*p*	*W*
No. of uses of personal spaces	-	-	-	4.5	2.36	4.18	4.83	-	-	-	-	0.0316	751.5
Length of time of using personal spaces	second	-	-	218.96	92.35	214.84	81.03	-	-	-	-	0.841	561
Average duration of each entry of personal space	second	-	-	68.02	56.33	130.79	97.87	-	-	-	-	0.0181	829
Size of group territory	m^2	0.90	0.81	0.44	0.40	0.41	0.46	0.0447	203	0.00251	210	0.654	158
Size of personal territory	m^2	1.41	0.53	2.88	0.69	2.62	0.80	2.64e-14	43	1.05e-09	80	0.3	663
Size of personal territory fallen in public space	m^2	1.41	0.53	1.44	0.61	1.39	0.49	0.410	510	0.849	594	0.324	659
Size of personal territory fallen in personal space	m^2	-	-	1.44	0.30	1.24	0.45	-	-	-	-	0.0411	745
Average distance	meter	0.99	0.31	2.31	0.52	2.29	0.47	8.57e-10	0	3.43e-09	2	0.760	135
No. of note edits done in group territory	-	44.71	69.88	12.29	16.11	7.17	10.54	0.0696	197	0.0101	218	0.373	169.5
No. of note edits done in personal territory	-	39.94	38.53	74.12	49.13	86.12	55.23	0.037	83.5	0.00925	68.5	0.593	128.5
No. of note edits done in other's territory	-	29.24	42.68	20.71	25.17	25.24	46.04	0.444	167	0.626	159	0.902	140.5
Time spent paying attention to collaborator	second	143.05	118.33	52.53	62.03	98.25	60.76	0.000147	888	0.248	673	0.00103	310
Times of drawing attention on collaborator	-	47.29	25.91	15.82	11.80	30.59	14.98	3.52e-07	993.5	0.00259	824	5.70e-05	249.5
No. of music interface additions	-	4.5	2.43	3.85	1.76	3.79	1.95	0.293	663	0.215	678	0.871	591.5
No. of music interface additions in personal space	-	-	-	2.18	1.47	2.06	1.48	-	-	-	-	0.743	604.5
No. of music interface additions in public space	-	4.5	2.43	1.68	1.37	1.74	1.76	1.52e-07	1001	5.93e-07	981.5	0.874	591
No. of note edits	-	127.82	63.19	120.74	49.56	129.56	51.39	0.825	596.5	0.754	552	0.540	527.5
No. of note edits done in public space	-	127.82	63.19	41.44	31.60	44.21	30.07	6.54e-09	1051.5	2.75e-08	1031.5	1.00	577.5
No. of note edits done in personal space	-	-	-	79.29	49.08	85.5	51.64	-	-	-	-	0.936	571

see CQ3 of Table 2. (3) Sense of collaborator's activities. Participants reported a proper level of sense of collaborator's activities in all conditions (C_P: $M = 6.9$; C_{PI}: $M = 7.1$; C_{PV}: $M = 7.2$), no significant difference between conditions was found. However, in the results of Comparison Questionnaire, a significant number (20 out of 42) of participants rated C_P as the session in which they felt least difficult to track collaborator's activities (Binomial Test, $0.48 > 0.33$, $p = 0.0384$, 1-sided), and significantly few (7 out of 42) of participants rated C_{PI} as the session in which it is least difficult to track collaborator's activity (Binomial Test, $0.17 < 0.33$, $p = 0.0132$, 1-sided).

Communication

Participants reported a good quality of communication in all conditions (C_P: $M = 7.07$, $SD = 2.25$; C_{PI}: $M = 8.02$, $SD = 1.86$; C_{PV}: $M = 7.83$, $SD = 1.99$), no significant difference between conditions was found.

Content assessment

When asked the satisfaction with the output, participants gave higher mean ratings in C_{PI} ($M = 7.92$) and C_{PV} ($M = 7.88$) compared with C_P ($M = 7.21$), however, Wilcoxon Rank Sum tests only show a trend (C_{PI} vs C_P: $W = 1077.5$, $p = 0.0746$; C_{PV} vs C_P: $W = 1062$, $p = 0.103$). Results of CQ1 shows significantly few participants (8 out of 42) believed it was in C_P that they made the most satisfying music ($0.19 < 0.33$, $p = 0.0317$, 1-sided), and a significant number of participants (22 out of 42) chose C_P as the session in which they made the least satisfying music ($0.52 > 0.33$, $p = 0.00835$, 1-sided), and a significantly small population (8 out of 42) chose C_{PV} as the session in which the least satisfying music was made ($0.19 < 0.33$, $p = 0.0317$, 1-sided), see results of CQ1 in Table 2.

Preference

A significant number of participants (37 out of 42) reported that there were differences between these conditions ($0.88 > 0.5$, $p = 4.434e\text{-}07$, 1-sided). Participants held positive attitude on the addition of personal spaces in both conditions (C_{PI}: $M = 6.19$, $SD = 2.67$; C_{PV}: $M = 6.88$, $SD = 2.33$), no significant difference. In the results of CQ, C_{PV} was rated as the best setting by a significant number of participants (21 out of 42; $0.5 > 0.33$, $p = 0.0187$, 1-sided), and a significantly few participants (8 out of 42) rated C_{PV} as the least best setting ($0.19 < 0.33$, $p = 0.0317$, 1-sided), see results of CQ5 in Table 2.

Contribution

For C_P, significantly many participants (22 out of 42) reported they had the least sense of self-contribution in this condition (Binomial Test, $0.52 > 0.33$, $p = 0.00835$, 1-sided), and significantly few participants believed they had the strongest sense of self-contribution in this condition ($0.17 < 0.33$, $p = 0.0132$, 1-sided). While a significant proportion of participants (22 out of 42) reported they had the strongest sense of self-contribution in C_{PV}($0.52 > 0.33$, $p = 0.00835$, 1-sided), no significant difference was found in the sense of co-workers' contribution.

Results of open-ended questions

At the end of PSQ, there were three open-ended questions, two of which are relevant to this paper: (1) Were there any differences between these sessions? If yes, please describe what was different? (2) Regarding the collaboration experience, do you have anything more to say? Some representative answers are shown in Table 3.

Activity assessments

In this section we report on measures focusing on the participants' interactive activities, see Table 4. Wilcoxon Rank Sum tests were run to compare conditions against each other, we chose Wilcoxon Rank Sum test as it does not require a normal distribution. Note 17 out of 21 groups used personal spaces in both C_{PI} and C_{PV}, however, four participants (1B, 2B, 7B, 15A) did not use personal space in either C_{PI} or C_{PV} or both, reasons include "feeling not safe to move" and "no needs to use". As here we want to investigate how participant's behaviour might change due to the use of personal space, and

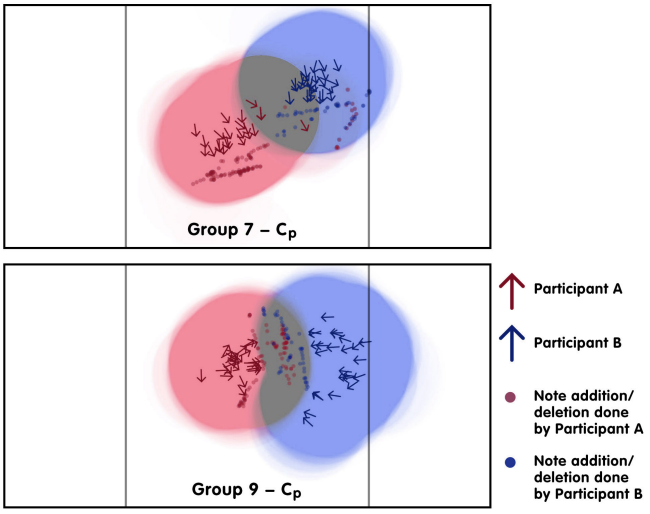

Figure 4. Visual traces of the participants' locations, directions and musical note edits (group7 and group 9 in C_P).

how personal space might be useful, the data of these 4 groups were excluded in the data shown in Table 4.

Times and amount of use

In the 8-minute (480-seconds) session, although there is no significant difference in terms of the length of time of using personal spaces (218.96 seconds in C_{PI} and 214.84 seconds in C_{PV}), participants entered personal space significantly more times in C_{PV} ($M = 4.5$) compared with C_{PI} ($M = 4.18$; Wilcoxon Rank Sum Test, $W = 751.5$, $p = 0.0316$). This results in a significantly shorter stay of each entry in C_{PI} ($M = 68.02$) compared with C_{PV} (M=130.79; $W = 327$, $p = 0.0181$). Although participants spent a certain proportion of time in personal spaces, they still stayed significantly longer in public space than they did in personal spaces (C_{PI}: $W = 769$, $p = 0.01878$; C_{PV}: $W = 780$, $p = 0.0128$).

Location and territory

To illustrate how participants used the space, we plot their locations, directions and musical note edits on a top view of the stage, see Figure 4, we call these plots visual traces. Specifically, the arrows were participants' locations at 20-second interval for ease of reading the diagram, and dots are the locations of participants' hands when making musical note edits. Research of table-top collaboration defines personal territory as a workspace close to the person and group territory as the central area or spaces between collaborators [41, 32, 33]. Following this, we dye the area within a 0.6-meter radius of the participants' locations (locations here are at 1-second interval for higher accuracy) with different tint colors (red for participant A's personal territory, and blue for B's) to indicate territories. We chose 0.6 meters as it falls into the range of close phase of personal distance, which permits one participant to touch each other or the same music interface [15], most of the musical note edits also fell inside this range.

(1) Distribution of locations and interactions. As tint color applied, the redder/bluer the area is, the more presence of the corresponding participant in that location is shown. The overlap is dyed with gray, indicating appearances of both participants, thus can be seen as group territory. Figure 5 shows the visual traces of all the groups, it can be seen that in C_P, apart from three groups (Group 4, 6 and 21), a significant proportion of groups (18 out of 21) developed fixed personal territory (red area for A and blue area for B) and group territory (Binomial Test, $0.86 > 0.5$, $p = 0.00074$, 1-sided). The C_{PI} and C_{PV} part of the visual traces proved a significant proportion of groups (17 out of 21) did use personal spaces when available ($0.81 > 0.5$, $p = 0.003599$, 1-sided).

(2) Sizes of personal/group territory. As shown in Table 4, participants formed a significantly larger size group territory in C_P ($M = 0.90$ m^2), than C_{PI} ($M = 0.44$ m^2) and C_{PV} ($M = 0.41$ m^2), an inspection of the visual traces (Figure 5) might also verify these results. Participants had an average of 44.71 group edits (edits done in group territory) in C_P, which is significantly more than that of C_{PV} ($M = 7.17$; $W = 218$, $p = 0.0101$), and a near-marginal significantly more than that of C_{PI} (12.29, $W = 197$, $p = 0.0696$).

When personal spaces were available, participants had significantly more music edits done in personal territory (both $p < 0.05$, see more details in Table 4) and formed a significantly larger size of personal territories in C_{PI} and C_{PV} compared with C_P (both $p < 0.001$, see more details in Table 4). However, if we deduct the part they formed inside personal spaces, there is no significant difference. We also found although the size of personal territory fallen in personal space in C_{PV} is significantly smaller than that of C_{PV} (C_{PI}: $M = 1.44$; $M = 1.24$ in C_{PV}; Wilcoxon Rank Sum Test, $W = 745$, $p = 0.00411$), the amount of music edits done in personal territories inside personal space in C_{PI} ($M = 74.12$) is similar to that of C_{PV} ($M = 86.12$).

(3) Average distance. No significant difference was found between the average distance of C_{PI} ($M = 2.3$ m, $SD = 0.52$) and C_{PV} ($M = 2.3$ m, $SD = 0.47$). However, compared to that of C_P (M = 0.99 m, SD = 0.31), the average distance is significantly larger in C_{PI} and C_{PV} (C_P vs C_{PI}: Wilcoxon Rank Sum Test, $W = 0$, $p = 8.57e\text{-}10$; C_P vs C_{PV}: $W = 2$, $p = 3.428e\text{-}09$).

Attention

(1) Time participants spent paying attention to each other. Though out the 480-second session, participants had their attention toward their collaborators' location for 143.05 seconds in C_P and 98.25 seconds in C_{PV}, both of which are significantly longer than that of C_{PI} (52.53 seconds). (2) Number of times of paying attention. Participants oriented their attention toward their collaborator for significantly different times, they did most times in C_P ($M = 47.29$), second most in C_{PV} ($M = 30.59$), and least in C_{PI} ($M = 15.82$; Wilcoxon Rank Sum Test, all $p < 0.01$, see detailed statistics in Table 4).

Contribution

(1) Number of music interface additions. Participants generated on average 4.5 interfaces in C_P, 3.85 in C_{PI}, 3.79 in C_{PV}, no significant difference was found. In C_{PI} and C_{PV}, participants had some of interface additions done in personal space, specifically, in C_{PI}, 1.68 interfaces were added in public space,

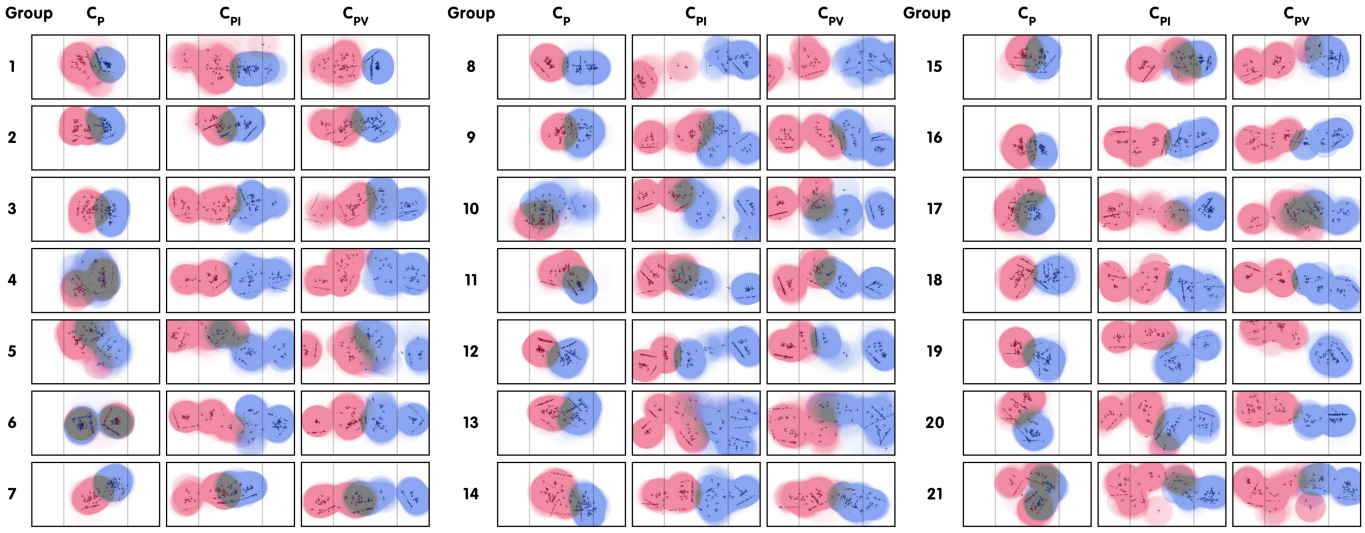

Figure 5. Traces of participants' positions and interactions.

and 2.18 in personal spaces, in C_{PV} 1.74 in public space and 2.06 in personal space, no significant difference was found either between these two conditions or between the public space and personal space in each condition, see more detailed statistics in Table 4. (2) Number of note edits. No significant difference was found in terms of the sum of note edits (C_P: M = 127.82; C_{PI}: M = 120.74; C_{PV}: M = 129.56). However, when classified by types of spaces, we found participants had significantly more note edits in personal spaces (C_{PI}: M = 79.29; C_{PV}: M = 85.5) than they did in public space (C_{PI}: M = 41.44; C_{PV}: M = 44.21; Wilcoxon Rank Sum Tests, both $p < 0.001$, see detailed statistics in Table 4). Considering participants spent significantly shorter time in personal spaces than in public space, this means participants were more efficient in making note edits in personal spaces.

DISCUSSION

Formation of territories

Formation of group territory and personal territory

Note in this section, we look specifically into the data of C_P rather than all the three conditions, as C_P was designedly experienced prior to the other two conditions to investigate the emergence of territories without impacts from the addition of personal spaces. As reported in the results of activity assessments (*location and territory*), in C_P all the groups formed a group territory and 18 out of 21 groups formed fixed personal territory. As shown in Figure 4 and 5, most of the interaction dots fall inside the personal territory with the same color or inside the group territory, indicating participants did most note edits inside their personal territory or group territory, they did fewer note edits inside each other's territory, which can also be approved by Table 4. We interpret this as participants had an ownership of their personal territories, music interfaces inside the personal spaces can be seen as personal interfaces, which limits other's access to these interfaces.

Participants formed not only personal territory, but also group territory, which matches the types of territory emerged in tabletop based collaboration [32]. While personal territory served to ease people's individual activities, group territory served a different function. Participants had equal access to group territory and the music interfaces located in group territory, there was no clear ownership of these interfaces, which might possibly ease the concern of editing on it. As a result, more music edits fell in group territory (44.71 in group territory *vs* 39.94 in personal territory *vs* 29.24 in other's territory). Participants seldom entered other's personal territories and fewer edits were done in other's personal territory, the majority of edits fell in either the personal territory or group territory. These territory-related behaviors match Taylor's claim that territorial behavior occurs during human interaction in territories, they build territoriality which gains them some degree of excludability of use, responsibility for and control over activities in these sites [36].

Our results showed that people not only build territoriality in real, but they also build it in virtual, and the territoriality serves a similar function. Thus, H1 is supported.

Two types of work configurations emerged in group territory

By inspecting the C_P part of Figure 5, we identified:

(1) *Side-by-side work configuration.* Seven groups (Group 5, 7, 10, 11, 12,15, 20) used this arrangement for working together, see Figure 5. Take Group 7 (Figure 4) as an example, participants faced roughly the same direction towards the music interfaces, and did note edits side by side. Inside the group territory, most of their note edits fell on one side of the group territory. Working side-by-side is common in daily working settings. Although due to distances or due to coworker's body as an obstacle, this configuration does not provide an equal access to the all parts of the shared working interface, being able to see the interfaces from the same side enables both participants to have a similar perspective on the interfaces, which is important for having a shared knowledge

of co-work undergoing. We think the reason for the emergence of this configuration is the flat music interface of LeMo, leading participants borrowed their daily life experiences. See Figure 3b, although the interface is 3D, it is still quite flat in *Matrix* mode.

(2) *Face-to-face work configuration.* As shown in Figure 5, participants of five groups (Group 3, 9, 16, 17, 18) worked face to face with music interfaces between them, see Group 9 (Figure 4) as an example. Different from side-by-side, the note edits spread more evenly in the group territory. In the real world, people do talk face-to-face, but people seldom work or interact with a vertical physical interface between them since a transparent interactive work interface is very rare in the real world and an opaque one will block their sight and face to face communication. While VR gives the opportunity of creating semi-transparent interfaces (Figure 1a), which enables participants to do so without obstructing sight between collaborators, thus, participants borrowed their experience of talking face-to-face. This configuration ensures both participants an equal access to the interfaces, enable them to see each other and the music interfaces at the same time, which can be helpful to track each other's activities. They can also interact with music interfaces without colliding with each other's bodies/avatars. However, this configuration has two limitations: i) The interfaces need to be specifically designed to be directionless, ensuring it can be manipulated from more than one direction; ii) Participants' view of the interfaces is reversed from each other's, which can be an obstacle to a shared knowledge of the co-work, e.g. with the music interface of LeMo, participants perceived the play-line moves oppositely.

Advantages of providing personal spaces

The times and length of using personal space, the notes edits and music interface additions done inside the personal space (Table 4), the note edits dots distributed inside the personal space (Figure 5) all demonstrate a significant proportion of groups (17 out of 21) used personal spaces to facilitate the task, and participants divided a considerable portion of time and work into personal spaces. More specifically, we argue providing personal spaces is useful in two ways:

A chance to explore own ideas freely

Earlier research focusing on privacy and awareness in collaborative music [13] shows participants interpreted personal space as an "area for experimentation and development, and participants often described their personal space as an area to 'prepare', 'sketch', 'test' and 'draft' contributions". Similarly, as shown in Table 3, and as reported in the subsection "*preference*" of section "*participant report*", most precipitants held a positive attitude to the additions of personal spaces in both C_{PI} and C_{PV}. Participants reported although C_P is good for people to work together, a workspace to work on their own is necessary (Participant 1A, 5A, 6A, 9B, 14B, 15A, see Table 3). This is because the additional personal space helped them to "focus on personal composition before sharing it", made it easier to "create own idea", and made it possible to "create something new without disturbing [their] collaborator and vice versa", see more detailed opinions in Table 3. To conclude, using personal spaces temporarily enables producing ideas independently, which may also increase the variety of diversity of final output, e.g. one participant reported *"not being able to hear my collaborator's work added an interesting dynamic to the piece"*. In this way these creations acted as useful intermediates which were then discussed, revised, and combined into the final group piece in public space.

A more efficient workspace

Results of activity assessments shown in C_{PI} and C_{PV}, when personal spaces were available, participants did more note edits in personal spaces although they spent significantly more time in public space, indicating that participants were more productive in personal spaces. One reason can possibly be that when being inside the public space, participants spent time on communication and discussion, while in personal space, they focused more on producing. Another reason is that when participants were inside their personal spaces, disturbing their collaborator and disturbance from their collaborator could be avoided, the disappearance of auditory disturbance and distraction made participants more focused on the development of ideas. Compared with C_{PV}, the invisibility of personal spaces in C_{PI} also removed the visual disturbance of co-worker's activities, and a few participants reported the removal was good for higher efficiency, the majority believed "being able to see each other was more efficient".

Providing personal space was believed to be helpful as it offered a chance to explore their own ideas and a more efficient workspace, these findings support H2. However, it should also be noted that due to the partially randomized sequence of experimental conditions (C_P always came first), the accumulated experience participants got in C_P may possibly increase their feeling in a positive way in later sessions, which weakens these supporting results to some extents.

Disadvantages of providing personal spaces

Despite the benefits brought by adding personal spaces, results show that the addition of personal spaces led to a smaller size of group territory, decreased number of note edits within group territory and greater distance between collaborators (Table 4). This is also approved by Figure 5, from which we can see that Group 4 and 8 did not form a group territory in C_{PI} and C_{PV}, and groups (e.g. group 1 and 13) formed a much weaker one. We argue the reasons for the weakening of group territory may be two-fold, first, when there were personal spaces, participants spent a considerable amount of time in the personal spaces, led to less presence in the public space, resulting in less chance to form group territory. The second reason is that personal spaces are on the opposite sides of the public spaces, for ease of accessing personal spaces, participants tended to manipulate the interfaces somewhere near their personal spaces, which led a more isolated situation (The average distance significantly greater in C_{PI} and C_{PV} compared with C_P). An increased distance between each other resulted in a smaller overlap of personal territory, namely a smaller group territory. Thus, we believe by shortening the distance between the collaborators' personal spaces, we can possibly reduce the negative effect, see 3 proposals shown in Figure 6.

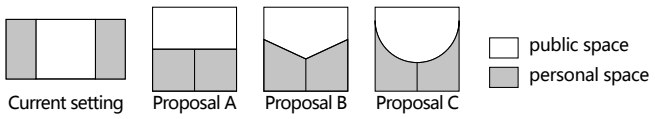

Figure 6. Proposals of different space settings.

Publicly invisible or publicly visible personal spaces

C_{PV} is preferred in general

A significant portion of participants rated C_{PV} as the best setting (see CQ5 in Table 4). Participants reported being able to see each other even when the collaborator was inside the personal space, made them feel "more communicated", "more comfortable", and C_{PV} provides both "privacy and teamwork equally" and made it easier to work either "individually or cooperatively", see Table 3.

Providing publicly visible personal space is found to be helpful to coordinate collaborator's activities [13]. Conversely, in C_{PI}, when personal space became invisible to collaborator, participants had significantly shorter length and fewer times of drawing attention toward their collaborator's locations compared with C_{PV} (statistics in Table 4), leading a weaker sense of coworker's presence and activities (CQ2 and CQ3 of Table 2), "weakest sense of communication with the partner", and a more "isolated" feeling. They reported they had to "talk more" to maintain a proper level of shared knowledge.

However, a few participants felt a different way about the invisible personal space. Participant 17A reported "*[he] definitely felt more isolated from each other, but [he was] kind of used to this in writing music*". Participant 19B reported C_{PI} helped her to think on her own, "without too much disturbance from the other". The additional visual cues in C_{PV} can also result in overloaded cognitive information, e.g. participant 9A reported C_{PV} was "distracting" and she preferred "audio communication" only. So as suggested by some participants, it would be good if people have a toggle to change the visibility.

The results of activity assessments (Table 4) show some differences of usage of these two personal spaces. Participants went to personal spaces significantly more times and stayed shorter for each entry, and paid significantly shorter attention to each other in C_{PI} compared with C_{PV} (Table 4), the reason can be that the opaqueness of personal spaces in C_{PI} made it impossible to glimpse what their collaborator was doing when being inside personal space, so they had to go back to public space more frequently to update work progress. While the visibility of personal space in C_{PV} enabled them to see each other and their work, update work progress and work a bit longer independently. Hence, the C_{PV} provides better support for collaboration compared with C_{PI}.

Overall influence on user behavior

Besides the differences mentioned above, similar to the findings in a non-VR context [13], no other different user behavior was found. This also indicates that both types of personal spaces can satisfactorily meet people's basic needs, which is to have a space to test and develop personal ideas without affecting each other. Thus, H3 is supported.

Key Findings and Implications for Design

In summary, the following are key findings from our results:

- With the emergence of group territory and personal territory, two working configurations appeared: *side-by-side work configuration* and *face-to-face work configuration*.
- Additional personal spaces supported individual creativity and increased efficiency with the cost of shrunken group territory and decreased number of note edits in group territory.
- Although both the publicly invisible and publicly visible personal spaces provide the basic functions properly, the visible one is preferred.

From these key findings we propose three design implications for Shared Virtual Environments (SVEs) focusing on supporting collaborative and creative tasks: i) The virtual shared working interfaces should be designed to suit *side-by-side work configuration* when direction forms an important factor of the working content (e.g. reading texts or diagrams), whereas transparent directionless interfaces can be applied to suit *face-to-face work configuration* to achieve a better face-to-face communication and an equal access to the shared interfaces; ii) Similar to existed findings in non-immersive media [13, 32], where possible, users should be provided with personal spaces which come with access control (and audio access control for music related task); iii) When personal space is provided, personal space with public visibility is preferred and thus should be prioritised, cf. [13].

CONCLUSION AND FUTURE WORK

In this paper, LeMo, an SVE that supports collaborative creativity has been presented. Based on it, we observed and measured the emergence of group/personal territory and territorial behaviour in collaboration in an SVE, and identified two types of work configurations in group territory. We found that providing personal working space is essential as it enables people to explore ideas without disturbing others. Differences between personal spaces with different visibility were found and discussed. Based on our findings, three implications for the future design of SVEs that focus on supporting collaborative tasks are proposed.

In the future, we are keen to further develop more settings of personal spaces, e.g. neighboured personal spaces, personal spaces with adjustable features (e.g. visibility, hearability and so on), and see how the effects on people's collaborative interaction in VR might change.

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