Braided Communications

ESA STAR RFP 3- 16884/21/NL/GLC

Enabling effective communication for human space exploration beyond Low Earth Orbit

Project Lead: Braided Communications Limited

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Contents

Overview

Communication between crew and ground on future deep space missions will be impacted by communication delay (signal latency), caused by the finite speed of light and radio waves across great distances. The one-way latency caused by the distance between the Earth and the Moon is about 1.3 seconds. The actual latency at lunar distances during the forthcoming Artemis missions is expected to be much higher due to the various signal processing steps associated with the digital communication protocols. Estimates currently vary up to 20 seconds one way. The Apollo missions, which used analog communication techniques instead of digital, were not subject to this additional delay.

For future missions to Mars the situation will be much more challenging. During transit the crew will experience continually increasing latencies starting at zero on departure and growing as they travel to Mars. On the surface, latency will still vary continuously as the Earth and Mars follow their separate orbits around the sun. The shortest possible latency to the Martian surface is about 3½ minutes one-way, the maximum is over 22 minutes. To date there has been little research into the consequences of communication delay on future crewed missions. However, like other challenges such as microgravity and radiation, it is unavoidable and will continuously impact the crew. It is expected to have significant operational impacts. Additionally, with the crew potentially unable to maintain meaningful connections with their loved ones on Earth, the consequences for crew health of prolonged isolation, amplified by the impact of signal latency, could seriously impact mission success.

Please see Appendix II for more details on latency to the Moon and Mars.

This investigation has been funded by ESA STAR RFP 3-16884/21/NL/GLC through its Open Space Innovation Platform (OSIP) programme (Contract Reference 4000136202/21/NL/GLC/ov). Braided Communications Limited, a UK-based SME, has developed a solution for mitigating communication latency, a tool called Space Braiding. It is the lead investigator and sole organisation providing deliverables to ESA under this research contract. This study has two components. Component A is an investigation into the impact of communication delay on the effectiveness of voice communication between crew and ground at the latencies that will be experienced on future lunar missions and in the near-Earth stages of transit for future Martian missions. It is preliminary data to answer the question “how far can humans travel from Earth before communication delay renders normal voice communication ineffective?” Component B is an investigation into the feasibility of a therapist on the ground using Space Braiding to deliver live sessions of psychological therapy to a crew member on or near Mars.

Component A shows two key results. First, as was hypothesised, the effectiveness of voice communication decreases as latency rises. Secondly, and unexpectedly, it indicated that communication at low levels of latency, less than 10 seconds, was less effective than at higher latencies of ~15 seconds. We hypothesise that at these lower latencies the participants are more likely to adopt the conversational behaviours they would under normal zero latency conditions, but that those behaviours then create difficulties such as ‘step-ons’ and ‘crossovers’ due to the latency. As these low latencies are exactly the range that is anticipated for Artemis missions it indicates a need for further urgent research. Component B shows a clear result that psychological therapy can be delivered by a ground-based therapist to a crew member operating under a five minute one-way latency using Space Braiding.

Latency: a hidden hazard

Latency will impact all communication between vehicle and Earth at all times during all missions beyond Low Earth Orbit. As such, its impact on future missions, both operationally and in terms of crew health consequences, will inevitably be significant. Yet it has been little researched to date, perhaps because it is in some ways less 'visible' than other factors. For example, we have all seen films of astronauts floating inside spaceships and so we all intuitively understand that microgravity will impact future crews. The same is true for radiation, something which is familiar from fields such as radiotherapy and nuclear power. And every mission to the ISS generates significant data on both these issues. In contrast, latency is not visible or obvious and is also not experienced at the ISS.

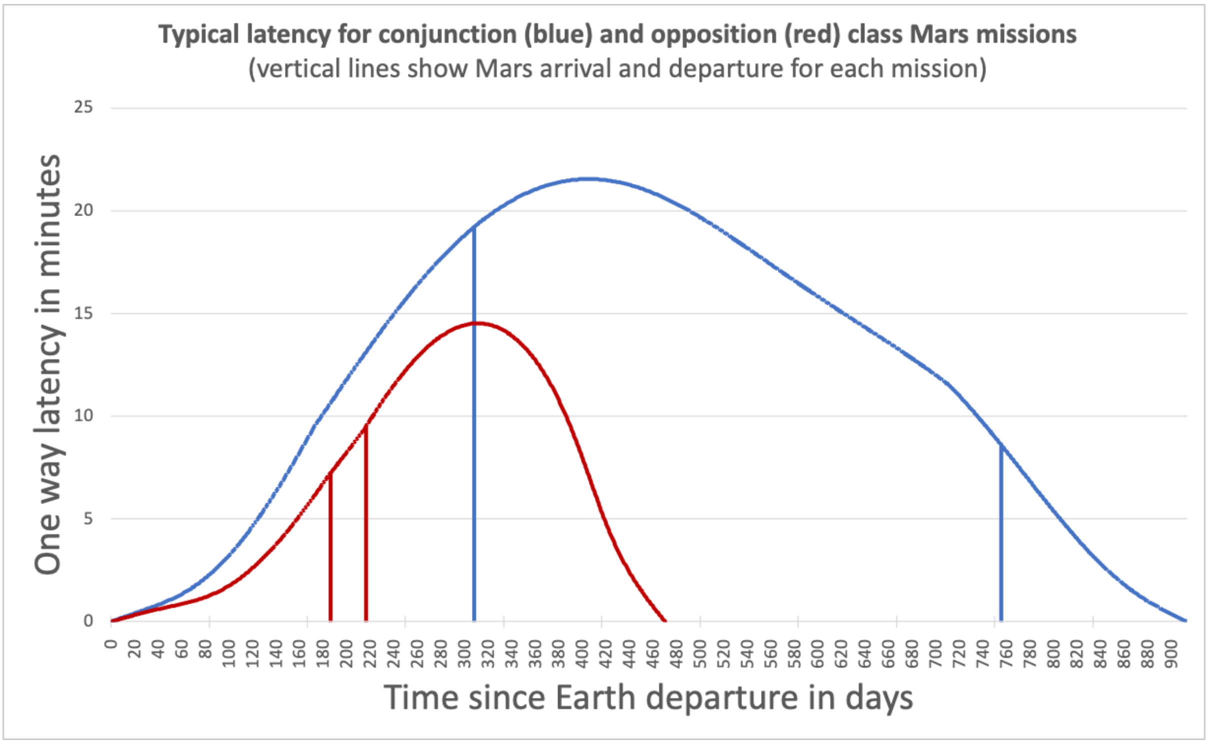
The initial research on time delayed communication confirmed assumptions that the detrimental impact of latency on communication effectiveness in future missions will be a significant problem requiring mitigation (FIscher & Mosier, 2014, 2016, 2022). Multiple risks and knowledge gaps across health and performance domains articulated in NASA's Human Research Roadmap are anchored in the problem (e.g. BMed 106 or Team 105). For example, a signal latency of 50 seconds, experimentally imposed during operational tasks on the ISS, produced significantly higher stress and frustration alongside major degradations in communication quality, crew morale and individual wellbeing (Palinkas et al, 2017). And an aquanaut, reflecting on the impact of communication delay on crew/mission control collaboration during a NASA Extreme Environment Mission Operations (NEEMO) analogue simulation, reported: "We looked at the voice loops, we looked at the text loops that occurred during these scenarios, and we saw afterwards that it was broken ten ways to Sunday. We were talking past each other; we were taking one response to mean, to be a response to a totally different question, you know, it was incredibly broken, and you could only see it when you took the time to really analyze it afterwards." (Vessey, Palinkas & Leveton, 2018).

This body of research has barely begun to scratch the surface of the latency challenge. And the scale of the challenge is substantial. The most significant latency yet experienced in a mission is that of the longest Apollo mission, Apollo 17, which lasted 12 days. Lunar transit (during which latency varied from zero to 1.3 seconds) was about three days each way. For six days the crew was in lunar orbit or on the surface, so communication was subject to a latency of 1.3 seconds one way (NASA, 1973).

The first Artemis crewed landing mission is currently expected to last between 26-42 days. As with Apollo, transit is likely to be three days each way so the Artemis mission might encounter maximum latency for up to 36 days, six times longer than Apollo 17. And as described above that latency is likely to exceed 1.3 seconds. When we consider a possible future mission to Mars the challenge becomes many orders of magnitude greater. The graph below shows the latency profile for two possible future missions to Mars. Opposition Class (short stay missions) are typically ~ 18 months duration with ~ 1 month on the surface. Conjunction Class (long stay missions) are typically ~ 36 months duration with ~ 15 months on the surface.

The scale of the challenge is evident from the below graphs, with many months when all communication will be subject to one-way latencies measured in minutes, not seconds. And that latency will be changing continually throughout the missions too, creating an additional variable and probably additional challenges. And the slope of both graphs varies continuously too, indicating that the rate of change varies too.

On the short stay mission profile (in red), latency is growing fast even after the crew has left Mars to begin their journey home. This is caused by the relative movements of Earth and Mars and it means, for a week or so after departure, the distance to home is actually increasing by eight Earth-Moon distances every 24 hours. The psychological impact of this on the crew and their loved ones on Earth may well be considerable. Future spaceflight analogue research will need to investigate the impact of latency as it changes across a mission profile.



Graphs created by Braided Communications Limited based on mission profiles and distance calculations provided by Space Exploration Engineering, LLC (www.see.com) and used with permission.

Component A: Edge of Voice

A1. Context

Synchronous voice communication - talking to each other - is a core component of human communication. On Earth, synchronous voice communication at a distance is available globally via the telephone network. The latency caused by distance is less than 0.1 seconds, even for two points on opposite sides of the globe, and so is imperceptible. Most people, therefore, find it completely natural to speak with contacts around the world just as they would with someone standing next to them in the same room, and so they apply the same behaviours and expectations to both types of communication. Those behaviours and expectations also apply to communication with crew on the ISS which, being in Low Earth Orbit, is only subject to distance latencies of about 0.001 seconds to the ground.

The Apollo missions proved that voice communication can also work at lunar distances (~1.3 seconds one-way delay), providing the participants had the discipline to wait for a reply, sometimes supported by operational procedures such as use of "over" at the completion of an utterance. Communication delays to the Moon during the forthcoming Artemis missions are expected to significantly exceed the 1.3 seconds experienced during Apollo, as described above. And in future missions to Mars, as the crew recedes from Earth that delay will become much larger.

This raises the question of how high latency can grow before we reach 'the edge of voice'? It is logical to expect that at low levels of latency voice communication will be rated as more effective and less effortful than at higher levels of latency. But what is the distance, or range of distances, where signal latency damages the effectiveness of voice communication such that it cannot be used in a synchronous, conversational, manner?

Following a review of the literature we have determined that this question has never been researched. We are keen to identify if those changes occur as expected, if they develop in a smooth gradient relative to changing latency or if there is a sudden drop-off in communication effectiveness and ramp up in perceived difficulty at a certain point or sub-range.

We have focused this study on a signal latency range between 3 to 25 seconds one-way. We chose this range because (i) it is higher than the ranges experienced during Apollo which was known to be workable (ii) it covers all ranges expected to be experienced during the future Artemis lunar missions and therefore has immediate relevance to mission planning and (iii) common sense indicates that at high latencies, perhaps ≥ 30 seconds, voice communication will have degraded from synchronous conversation to the asynchronous exchange of voice notes.

A2. Design

A small-*n*, within-subject, repeated measures experimental design was used in which participants completed the same outcome measure after experiencing different intervals of the independent variable (different sizes of signal latency). Participant pairs completed two live voice communication sessions, each one with a different task scenario and different signal latency applied to their verbal utterances.

The two scenarios used in the task were counterbalanced so that half of the pairs used the Lunar scenario in the first communication session followed by the Houdini scenario (both described below, in the appendix) in the second communication session. This sequence was reversed for the other half of the participant pairs. The sequence of latencies was also similarly counterbalanced so that half the pairs experienced low followed by high latency and the sequence reversed for the other half of the pairs.

Ethics

The study protocol and associated materials were thoroughly reviewed, and ethics approval granted, by David Carpenter, ethics reviewer on behalf of the Association of Research Managers and Administrators ARMA (ARMA), UK, in June 2022, before commencing recruitment. The ethics final report is provided in Appendix D. A Life Sciences Research Protocol (LSPR), provided alongside this document, describing the study and confirmed ethical approval, was also submitted to the ESA Medical Board. All personally identifiable data was pseudonymised during the study and on the completion of data collection, was deleted. The exception is a list, held securely, where individual participants explicitly requested in writing to have their email address kept on file to be sent the written-up research paper when it is available.

Participants

Thirty-six healthy adult volunteers from aerospace medicine student populations across the UK, Europe, India and the Americas were recruited. Most had some connection to the Students for the Exploration and Development of Space (SEDS) and/or the Aerospace Medicine Student and Resident Organisation (AMSRO). From this pool, participants were randomly matched in pseudonymised pairs, according to when they were available in their schedules. We initially matched sixteen participants into eight pairs to proceed into training and the experiment. We later matched one additional pair when one of the original pairs was unable to enter the experiment. All participants have been sent a formal letter they can reference in their CVs thanking them for volunteering and detailing the study. The recruitment flyer is provided in Appendix C.

Procedure

For training, participants attended a video meeting with the research investigators, Rob Brougham and Drew Smithsimmons, comprising a powerpoint presentation of brief, relevant, background information and then participating in short demo sessions, in their pairs, using the experimental communication tool they will be using in the experiment, Latency Governed Voice (LGV).

LGV is a web app that applies simulated signal latency to a live voice conversation. It was conceived and designed by one of the authors (RB) and built by a specialist software house in the UK named GravityWell. A description of LGV is given in Appendix B. Participants were instructed to use a wired headset with a built-in microphone and run the application on the Mozilla Firefox browser which, in earlier testing, was confirmed to be optimal for LGV.

Each pair of participants had a 60-min time slot scheduled for the experiment consisting of two 20-min live voice conversations, using LGV, punctuated by time to complete the outcome measure. One voice conversation had a lower signal latency applied and the other a higher signal latency applied within the range of 3-25 seconds one-way. As each person in the pair would independently report their outcome measures at the end of each 20-min conversation and as each set of outcome measures would ultimately generate one data point for analysis we were targeting the overall creation of 32 data points, as shown here:

Low latency scenario			**High latency scenario**			Total data points expected per pair
Latency	Scenario	Data points expected	Latency	Scenario	Data points expected	
5 sec	Lunar	2	25 sec	Lunar	2	4
7 sec	Lunar	2	20 sec	Lunar	2	4
9 sec	Lunar	2	15 sec	Lunar	2	4
3 sec	Lunar	2	10 sec	Lunar	2	4
5 sec	Houdini	2	25 sec	Houdini	2	4
7 sec	Houdini	2	20 sec	Houdini	2	4
9 sec	Houdini	2	15 sec	Houdini	2	4
3 sec	Houdini	2	10 sec	Houdini	2	4
						32

Task

To generate a context for communication that has relevance to space operations we used two space-based scenarios (a lunar and an asteroid surface mission) with the additional feature of providing each participant with an 'urgent update' as the conversation progressed, in order to simulate an evolving situation with greater communication demands. In both scenarios, the participants must engage in discussion to respond to an urgent situation requiring them to collaboratively plan and problem-solve with limited resources (details of which were provided in the scenario summaries).

The scenarios, procedural info and LGV logins were emailed to participants the day before the experiment while the urgent updates were emailed during the experiment. The Lunar and Houdini scenarios place participants each in the role of crew and mission control. Between the first communication session and the second communication session, each using a different scenario, the participants swapped roles. The scenarios and urgent updates are provided in Appendix D.

Outcome measure

After both time-delayed voice communications, the participants completed a Google Form, rating different qualities of the communication that fall into two domains: one exploring the effectiveness and effortfulness of the communication and the other exploring the impact of latency. The outcome measure contained the following questions for the participants to respond along bipolar scales. These scales have negative and positive end points that switch randomly from right hand side to left hand side between questions to focus the participants on careful, precise, responses.

Domain A

The conversation felt…

Q1	Natural	1	2	3	4	5	6	7	8	Unnatural
Q2	Inefficient	1	2	3	4	5	6	7	8	Efficient
Q3	Complicated	1	2	3	4	5	6	7	8	Straightforward
Q4	Disjointed	1	2	3	4	5	6	7	8	Orderly
Q5	Coherent	1	2	3	4	5	6	7	8	Incoherent
Q6	Demanding	1	2	3	4	5	6	7	8	Effortless
Q7	Effective	1	2	3	4	5	6	7	8	Ineffective
Q8	Unclear	1	2	3	4	5	6	7	8	Clear
Q9	Easy to follow	1	2	3	4	5	6	7	8	Hard to follow

Domain B

To me the time delay was…

Q1	Distracting	1	2	3	4	5	6	7	8	Not an issue
Q2	Inconsequential	1	2	3	4	5	6	7	8	Significant
Q3	Apparent	1	2	3	4	5	6	7	8	Inconspicuous

A3. Results

Sample size

Due to the small sample size, the data reported is descriptive.

Compliance

As described above we were targeting the generation of 32 data points. However during the experiment we encountered some technical and personal (participant illness) issues which impacted our ability to collect data. Ultimately six pairs successfully completed the experiment at both their allocated latencies, resulting in the creation of 24 out of 32 targeted data points (75%). These data points were distributed as follows across the experimental latencies:

Latency	3 sec	5 sec	7 sec	9 sec	10 sec	15 sec	20 sec	25 sec
Data points targeted	4	4	4	4	4	4	4	4
Data points obtained	4	4	2	2	4	2	2	4

Conversational Positivity Score Analysis

Our analysis focussed on analysing the “overall positivity” of each conversation. For each question one end of the scale was a positive answer (i.e., the participant felt the conversation was effective) and the other end was a negative answer (i.e., the participant felt the conversation was ineffective). However, as described above, the positive and negative endpoints were varied at random across the questions, to ensure participants fully read and considered each question before responding. In each case there were eight possible scores, from 1 to 8.

The midpoint for each question was therefore 4.5 and each participants’ score could be compared against the midpoint to give a rating that we named the “Positivity Score.”

The positivity score could therefore range from +3.5 (if they had chosen the far positive end of the scale) to -3.5 (if they had chosen the far negative end of the scale).

For each participant, in each of their two experimental sessions, this process was applied to their answers to all questions and the positivity scores then averaged to give an overall positivity score. A worked example is shown in the table below, where the overall positivity score is labelled “Average:” and is 2.417 in this case.

											MidPoint	Participant response	Positivity score
The conversation felt:	Natural (1) to Unnatural (8)	1	2	3	4	5	6	7	8		4.5	3	1.5
	Ineficient (1) to Efficient (8)	1	2	3	4	5	6	7	8		4.5	6	1.5
	Complicated (1) to Straightforward	1	2	3	4	5	6	7	8		4.5	7	2.5
	Disjointed (1) to Orderly (8)	1	2	3	4	5	6	7	8		4.5	7	2.5
	Coherent (1) to Incoherent (8)	1	2	3	4	5	6	7	8		4.5	2	2.5
	Demanding (1) to Effortless (8)	1	2	3	4	5	6	7	8		4.5	5	0.5
	Effective (1) to Ineffective (8)	1	2	3	4	5	6	7	8		4.5	2	2.5
	Clear (1) to Unclear (8)	1	2	3	4	5	6	7	8		4.5	2	2.5
	Hard to follow (1) to Easy to Follov	1	2	3	4	5	6	7	8		4.5	7	2.5
To me the time delay was	Distracting (1) to Not an issue (8)	1	2	3	4	5	6	7	8		4.5	8	3.5
	Significant (1) to Unconsequential	1	2	3	4	5	6	7	8		4.5	8	3.5
	Inconspicuous (1) to Apparent (8)	1	2	3	4	5	6	7	8		4.5	1	3.5
												Average:	***2.417***

This process was completed for all participants and for all conversations. The results are shown in the table below, with the colour coding later applied to the pairs in the graphs that follow.

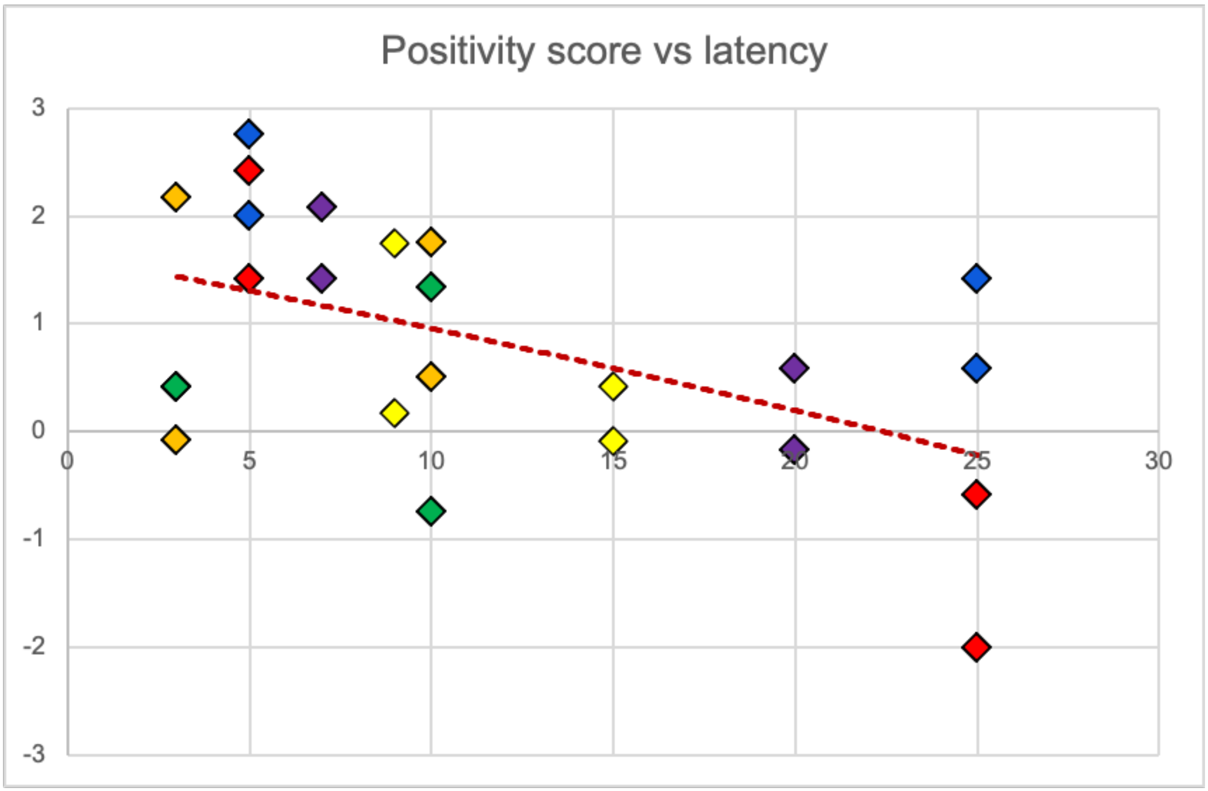
The two right hand columns in the table below are therefore the “overall positivity score” in each case. The example table above came from:

- Pair: One
- Scenario: Lunar
- Latency: 5 seconds
- Participant: ground

And you can see the “overall positivity score” of 2.417 in the table below, as calculated in the worked example above.

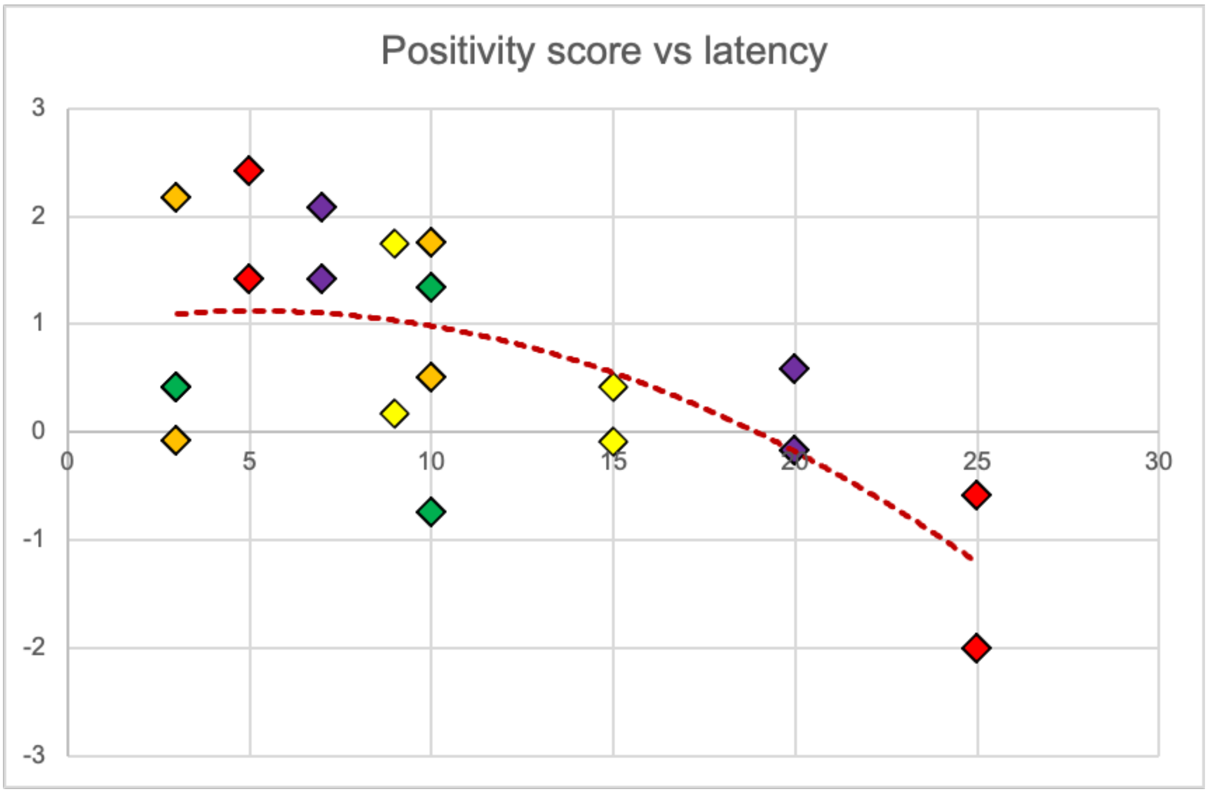
Pair	Scenario	Latency	Ground	Crew
One	Lunar	5	2.417	1.417
One	Houdini	25	-2.000	-0.583
Three	Lunar	9	0.167	1.750
Three	Houdini	15	0.417	-0.083
Four	Lunar	3	0.417	0.417
Four	Houdini	10	-0.750	1.333
Five	Lunar	5	2.750	2.000
Five	Houdini	25	1.417	0.583
Eight	Lunar	20	-0.167	0.583
Eight	Houdini	7	2.083	1.417
Nine	Lunar	10	0.500	1.750
Nine	Houdini	3	2.167	-0.083

These results were then plotted on a simple scatter plot and a 2nd order polynomial line of best fit added as shown here:



Please note that for pair Four (green) at latency = 3 seconds the scores of both participants were identical, so there are two green data points at 3 seconds, one directly overlying the other.

It is reasonable to consider that pair five (blue) could be an outlier. Their scores at 5 seconds latency were more positive than other pairs' scores at 3, 5, and 7 seconds and their scores at 25 seconds were more positive than other pairs' scores at 20, 15, 10 and 9 seconds. We therefore created a version of the same graph with pair five excluded:



The trend line here appears to be indicating a possible counterintuitive effect that scores may be more negative at low latencies, before becoming more positive at ‘mid’ latencies then trending downwards at ‘high’ latencies. However, that indication should be set in context given the small sample size and the fact that in this initial design all participants were tested at low and high latencies but not all participants were tested at every level of latency.

To investigate this in more detail we reviewed qualitative feedback. The qualitative feedback from several participants did seem to confirm this factor. Specific quotes included:

“the shorter latency was more difficult/unnatural because there were instances of talking over each other and therefore missing some information in conversations”

“the chances of overlap (for example having to continue talking because I was sending out an emergency message while I simultaneously have to listen to the other person's message which arrived mid-sentence of my talking) was much higher with lower latency than with longer latency periods. But this just had to do with higher probability of overlap. Could also be owing to the idea that with lower latency we try to make it as one-on-one trying to almost match it to a real time conversation and with higher latency we tend to have a quiet understanding of having to wait.”

[the low latency communication] *“...was so much closer to a conversation without time delay that I expected it to flow a little better, so we kind of resorted to a more normal conversation pattern at first (smaller bits of info, no “over” to indicate that we finished the sentence, etc) that wasn’t helpful at all so we then tried the same approach we used with the longer latency (longer info in 1 message & wait for the other person to reply) without the “over” since it felt* *repetitive and time-consuming at the time. That was a bit better but still a bit confusing at times, especially with the emergency info that we needed to communicate."*

A4. Discussion

Indication of deterioration

The first scatter graph, above, indicates conversation becoming more challenging as latency increases. With the crewed Artemis missions only a few years into the future, it is important to fully investigate this relationship and understand how to mitigate the impact, where possible. Whilst the overall trend is clearly negative - the higher the latency the less effective the conversation - there is also an indication that the rate of deterioration may accelerate significantly at latencies above 10 seconds. This is an indication only at this stage of course. Partly because the missing data means these latency ranges are not fully examined and partly because this trend is only clearly indicated when one pair's scores are removed as outliers. Based on the data we have this is reasonable, but we acknowledge that this is a small data set and further data might show the outlier to be normal. Given that some current estimates indicate that the lunar Artemis latency may reach almost 20 seconds one way this may represent a significant hazard.

Indication of unexpected problems at lower latencies

Despite the overall trend of increasing complexity aligned with increasing latency we saw indications of a reversal of that trend at low latencies (< 5 seconds). The qualitative statements supported that finding. Although not previously anticipated the qualitative statements do point towards a logical mechanism. At low latencies participants 'forget' the challenges of their environment and so begin to behave conversationally as if they are in a 'normal' zero latency environment. This can work temporarily, when perhaps natural thinking pauses align with the latency, but inevitably will cause difficulties when the latency does not align and causes 'crossovers' (where comments are transmitted from both ends simultaneously) and 'step ons' (where a comment is received from the far end whilst the other person is actually speaking). Again, given that this range is almost certainly going to be included within the lunar Artemis latency this may represent a significant hazard.

A5. Conclusion

The outcome data initially supports the primary hypothesis, tentatively due to sample size, and also gives a preliminary signal of two additional factors that may be relevant to the crewed Artemis lunar missions anticipated for ~ 2025. Specifically, that there may be an accelerated deterioration of verbal communication effectiveness somewhere above 10 seconds latency and also that there may, counterintuitively, be a deterioration of effectiveness at latencies below ~ 5 seconds too. Possibly due to people mistaking low latency for zero latency and adopting corresponding behaviour. It is normal for people to expect a zero latency context in most of their day to day lives and that could present a risk of ineffectiveness in human communication at low latencies. This phenomenon stands in contrast to the idea that inefficiencies in human communication are only caused by large latencies.

All of the data, results and indications must be caveated with the limitations of the small-n study design. The remote, online, nature of the study meant that technical issues could not practically be resolved, and participants' background and experiences inevitably varied significantly and did not include any operational mission experience.

Recommendations

Further research on this topic would be beneficial, especially when considering that crewed Artemis missions are expected to depart for the Moon in just a few years and those crews will experience latencies of up to 20 seconds for all communication with Earth for a month or more.

This study observed a possible effect that is deserving of more in-depth investigation. We recommend those future research studies adopt some or all of the following recommendations:

- They should include a larger participant population.
- They should be completed in a controlled analogue or laboratory environment.
- Participants should be 'professionals' with relevant mission training or expertise (accepting personnel are not yet trained in long latencies, an issue these investigations will help to address).
- Permission should be obtained from the participants to save the recordings of the dialogs for sentiment and other analysis, within the parameters of GDPR.
- Performance across different conversational types and situations should be studied. For example, there may be significant differences between effectiveness of private medical conferences vs personal conversations with family vs conversations with mission control. Equally (as we studied at a very rudimentary level) factors such as the sudden emergence of new, possibly emergency, information may affect performance.

Component B: High-latency psychological therapies

B1. Context

The objective of this component was to conduct a preliminary investigation into the feasibility of delivering live sessions of high-intensity evidence-based psychological therapy between a clinician on Earth and an astronaut in transit to Mars under conditions of very large signal latency (in this instance, a 5-min one-way comms delay). In any future Martian mission, given the duration and the challenges of the mission, crew will require support from the ground to promote psychological health, monitoring to track psychological health and effective interventions to counteract any episodes of poor psychological health.

Human spaceflight is hazardous to health across three primary, interacting, domains: isolation, microgravity and radiation (BMed108, NASA, 2022), all of which are exacerbated by the prolonged and intensified exposure inherent to long-duration exploration class missions. Within the core of the isolation domain, signal latency is both a risk to crew health and an obstacle to clinical health support from the ground.

Signal latency has been shown to severely disrupt operational communications (Fisher & Mosier, 2016). Conventional modes of social interaction under conditions of signal latency, such as email and messaging, do not enable communication synchrony. Synchrony, in this context, can be defined as a shared focus of attention and behaviour that is coordinated by a shared rhythm and maintained through a period of time (Chetouani et al., 2017). Synchrony in a communication channel is required for the people communicating with one another to experience co-presence; the experience of being psychologically connected to another person in a shared present moment, even if that other person is not physically proximal (Oh et al, 2018).

The quality of the therapeutic alliance between a psychological therapist and person engaging in that support with them predicts the outcome of the collaboration (Barber et al, 2000). Synchrony is central to the therapeutic alliance because it plays a key role in establishing rapport (Vacharkulksemsuk and Fredrickson, 2012), perspective taking (Wheatley et al., 2012), and the development of adaptive emotion-regulation (Feldman, 2007). Signal latency poses a formidable challenge to interpersonal synchrony and, therefore, to effective psychological therapy. In human deep space exploration, data will be exchanged between vehicle and ground at the fastest possible rate but being able to send information a-synchronously does not translate into meaningful social stimulation (Dunbar, 2012) and can intensify the experience of isolation (Schultze, 2010).

Due to the large signal latencies inherent to deep space exploration, live psychological therapy sessions between a psychological therapist and crew member appear impossible at first glance. However, the capacity of Space Braiding to enable effective synchronous sessions of dialogue under conditions of high-latency, characterised by interpersonal synchrony (defined below), opens up the possibility of effective, synchronous, therapeutic collaborations if clinicians consider it feasible to deliver their established interventions through this novel communication medium.

B2. Design

A small-n participatory action research design was used with a group of expert clinicians with extensive expertise in delivering high-intensity evidence-based psychological interventions through the medium of computer-mediated communication. Action research is a methodology primarily used in the social sciences. Participatory action research enlists participants as co-researchers from within a community of practice (psychological therapy in this case) to investigate a phenomenon relevant to their expertise and capturing their reflections. Pairs of participants completed the same questionnaire after two simulations in the form of clinical role-plays, whilst subject to 5 minute one way signal latency, using Space Braiding, described below.

Consideration was given to the creation of a control condition for this study but it was concluded that no appropriate control could be created. The only possible controls would deliver therapy via time delayed voice or time delayed messaging and would need to mirror the key parameters of five minute one way latency within a maximum sixty minute therapy session.

In these scenarios the opportunity for communicating is profoundly reduced. Eighty percent of the communication session would involve the participants waiting in silence. If one person asked their partner a question, they would be forced to wait at least twelve minutes to receive the reply (as below).

Time	Event
00:00 - 01:00	Clinician opens a therapy session with an initial question in one minute. Clinician now waits.
01:00 - 06:00	Initial question travels to patient under a five minute one-way latency. Clinician has been waiting five minutes by this point.
06:00 - 08:00	Patient receives the initial question and creates a response in two minutes. Clinician has been waiting seven minutes by this point.
08:00 - 13:00	Initial response travels from patient back to clinician under a five-minute one-way latency. Clinician has been waiting twelve minutes by the time they have heard every word of the patient's initial reply.

A sixty-minute communication session would afford the participants only five opportunities to complete this serve-and-return interaction within small moments of listening and responding separated by large periods of waiting. Such a channel, whether text- or audio-based, cannot reasonably be considered a suitable control for Space Braiding, a communication channel that affords continuous interaction for the whole sixty minutes, and does not represent a form of contemporary best practice for human communication under latency that could serve as a useful reference point either.

Ethics

The study protocol and associated materials were thoroughly reviewed, and ethics approval granted, by David Carpenter, ethics reviewer on behalf of ARMA, UK, in June 2022, before commencing recruitment. The ethics final report is provided in Appendix D. In the following results section, the participants' initials have been pseudonymised and no personally identifiable data is being shared.

Participants

A group of highly experienced psychological therapists were recruited who are expert current practitioners in delivering evidence-based psychological therapies via live, typed, digital modalities (n=6). They were given a small honorarium of a £100 voucher each to recognise the cost of their professional time that, given the current pressure on mental health services post-Covid, was a challenge to secure and schedule. Their input amounted to 3.5 hours, scheduled as one-half day of activity, with a 30 min comfort break between the experimental time-delayed psychological therapy sessions.

Procedure

The clinicians were asked to select a component of an evidence-based psychological intervention from within the contextual-behavioural and cognitive-behavioural approaches. For those that used traditional second-wave cognitive-behavioural therapy, a common component was cognitive restructuring. Unhelpful cognitions causing obstruction to the patient's objectives are identified, challenged and alternative, more useful, cognitions are evaluated (Beck, 1979). For the clinicians that chose a contextual-behavioural therapy, several chose to focus on cognitive defusion, a skill very different to the former, where unhelpful cognitions are noticed and not challenged but distanced from so that the person can return their attention and action to valued-based behaviours rather than being caught up internally in their own thoughts.

They were asked to select a component they considered themselves to be extremely familiar with and proficient in delivering through their typical computer-mediated modality. The typical modality for this group of clinicians is internet-enabled cognitive-behavioural therapy (ieCBT) which is a live, high-intensity, typed, remote, zero-audiovisual and zero-latency modality). The clinicians also provided a 'case vignette' - an anonymised summary of a real psychological difficulty, from clinical practice, that their partner in the simulation, the 'patient', would use.

The participants were randomly arranged into three pairs and attended a one-hour training session, by video, with the principal investigator comprising a powerpoint presentation of brief, relevant, background information and a demo of the communication tool they will be using, Space Braiding (described in Appendix A), followed by a short practice session in their pairs on a neutral topic (e.g. favourite holiday taken, types of books they like to read etc) to have a direct experience of using the tool and ask any questions. Having completed training and practice, the participant pairs proceeded into the experimental task itself, two instances of a simulation; a clinical role-play. Training was necessarily minimal to suit the clinicians schedules, it was sufficient for them to operate Space Braiding and engage in the role-play. However, Space Braiding uses a dialogue structure that is novel and individual differences have been observed in the speed and dexterity that participants become proficient. It is reasonable to assume that such differences influence this preliminary data set. The study was not focused on mapping this range of individual differences. It is reasonable to predict that despite these differences, a broad increase in competence and clinical outcomes would be observed in a group of clinicians who are experienced in using Space Braiding.

Clinical role-play is a fundamental and well-understood method used to build core skills, explore clinical presentations (psychological health and distress) and test new techniques within psychological therapies. It is a method that the principal investigator (DS) and all the participants have extensive experience with.

Task

All six clinical role-plays had a sixty-minute duration and were conducted live, remotely, using Space Braiding; a typed-only computer-mediated medium with no audio or video component. Space Braiding enables high-latency synchrony and, in terms of human communication between vehicle and ground, NASA research (Fisher & Mosier, 2022) indicated the communication technology facilitates more effective operational communication under conditions of major signal latency compared to current practice, whilst UKSA research conducted with space health experts from UCL (Braided Communications, 2022) indicates Space Braiding facilitates faster collaborative problem-solving for no additional effort under comparable conditions.

A five-minute one-way signal latency was applied to all communication sessions, equivalent to 89.9m km of distance between ground and vehicle. This is neither the smallest, nor the largest, signal latency that will occur across a Mars mission profile, but sufficiently large to have genuine fidelity to deep space exploration and sufficiently manageable for the participants without scheduling sessions longer than 60 mins which would have been a challenge to fit into their schedules.

The participants had no other contact with each other during this phase. Each pair of participants were labelled Therapist A and Therapist B, with Therapist A in the role of the clinician, Therapist B in the role of the patient and then, in the second role-play for each pair, they swapped those roles.

Outcome measure

After both simulations, the participants completed a Google Form, rating the feasibility of Space Braiding as a mechanism for the delivery of a recognisable component of evidence-based therapy. The questions explore different qualities of the communication, but fall into two domains: one exploring the feasibility of using Space Braiding to deliver the component of therapy they selected and the other focusing explicitly on the impact of latency. The questionnaire contained the following questions for the participants to respond along bipolar scales. These scales have negative and positive end points that switch randomly from right hand side to left hand side between questions to focus the participants on careful, precise, responses.

<u>Q1 – 6: Completed after being in the role of the clinician delivering support</u>

[Q1] How effective did you find this medium for delivering the therapy component?

Q1	Ineffective	1	2	3	4	5	6	Effective

[Q2] Compared to your usual practice, how difficult did you find it to deliver the therapy component in this medium?

Q2	Not difficult at all	1	2	3	4	5	6	Very difficult

[Q3] How different did you find it working in this way, compared to your usual practice?

Q3	No difference	1	2	3	4	5	Very different

Note on [Q3], having had the opportunity to consider the data, the positive and negative pole on this question was insufficiently clear from the perspective of a clinician working in a computer-mediated modality. As such, this section of data has been excluded from the key results but is addressed in the discussion section below.

[Q4] How noticeable was the time-delay?

Q4	Not noticeable	1	2	3	4	5	6	Extremely noticeable

[Q5] How did the time-delay negatively impact the interaction?

Q5	Extremely negative	1	2	3	4	5	No negative impact

[Q6] Do you think therapy using braiding offers new opportunities compared to traditional internet-enabled methods?

Q3	Many new opportunities	1	2	3	4	5	No new opportunities

Note on [Q6], this question was asked given the importance of spaceflight research to drive innovation that helps to solve intractable terrestrial problems and the insight of the participant group into solving those problems with technology. It is therefore addressed in the discussion section but has been excluded from the key results in terms of feasibility.

<u>Q7 – 11: Completed after being in the role of the person engaging in support</u>

[Q7] How effective did you find this medium for engaging with the therapy component (the new skill being introduced)?

Q7	Ineffective	1	2	3	4	5	6	Effective

[Q8] How much did this feel like a real, live, conversation between the two of you?

Q8	Not at all	1	2	3	4	5	6	Very much

[Q9] How noticeable was the time-delay?

Q9	Not noticeable	1	2	3	4	5	6	Extremely noticeable

[Q10] How did the time-delay negatively impact the interaction?

Q10	Extremely negative	1	2	3	4	5	No negative impact

[Q11] Did you feel another human being was truly present with you in a shared moment?

Q11	Not at all	1	2	3	4	5	6	Yes, completely

B3. Results

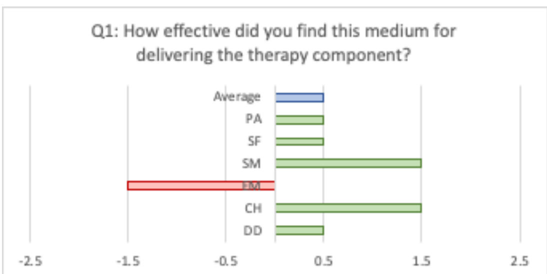
Sample size

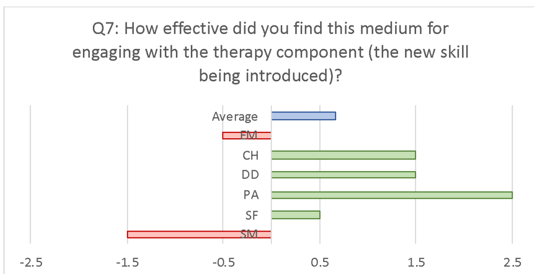
Due to the small sample size, the data reported is primarily descriptive.

Effectiveness

After being in the role of the clinician, participants were asked: ‘How effective did you find this medium for delivering the therapy component?’ (Q1). Their responses were along a bipolar scale between ‘ineffective’ at one end to ‘effective’ at the other. After being in the role of the person receiving psychological support, the participants were asked: ‘How effective did you find this medium for engaging with the therapy component (the new skill being introduced)? (Q7). Their responses were along an identical scale in this instance.

Four out of six participants reported Space Braiding to be an effective medium for the delivery of live sessions of evidence-based psychological therapies under the condition of a five-minute one-way latency. Five out of six reported effectiveness from the perspective of the clinician providing psychological support and four out of six reported effectiveness from the patient’s perspective.



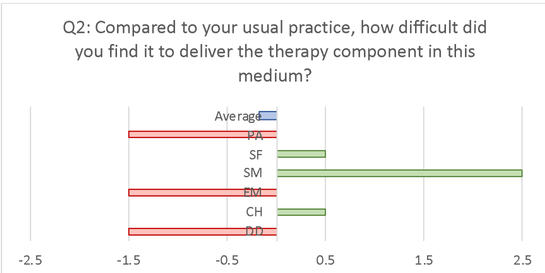


Difficulty

After being in the role of the clinician delivering support, participants were asked: ‘Compared to your usual practice, how difficult did you find it to deliver the therapy component in this medium? (Q2). Their responses were along a bipolar scale between ‘not difficult at all’ at one end to ‘very difficult’ at the other.

Usual practice for this clinical group, as described above, is internet-enabled cognitive behavioural psychotherapy. ieCBT requires clinicians and patients to log into a secure, clinical, platform that supports live text-based sessions of high-intensity psychological therapy, typically sixty-minutes long. In those sessions there is no audio and no video, only live written dialogue. Relating that to Space Braiding, these clinicians are highly experienced in delivering effective therapy in one braid, one live written thread, across multiple topics. What is novel for them is arranging those topics into separate braids they engage with, one at a time, in a timed sequence anchored in an underlying communication delay.

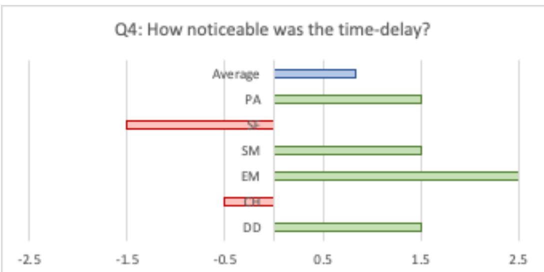
The level of difficulty experienced was largely individual to each participant with a minor directionality towards the negative pole, overall. However, in the first round of communication sessions, two out of three therapists reported difficulty whereas in the second round only one out of the three did.

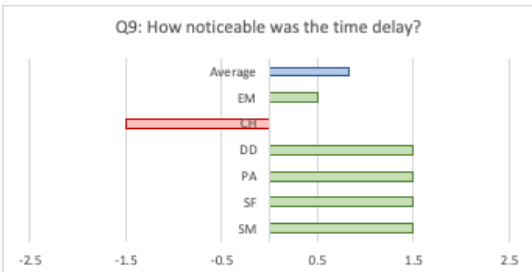


Perception of latency

After being in the role of the clinician, participants were asked: ‘How noticeable was the time-delay?‘ (Q4). Their responses were along a bipolar scale between ‘not noticeable’ at one end and ‘extremely noticeable’ at the other end. After being in the role of the patient, the participants were asked the same question (Q9) with the same bipolar scale for their responses

Four out of six participants in the patient role reported the experience of the five-minute one-way signal latency as not being noticeable during their live communication sessions. Five out of six participants in the role of patient reported this.

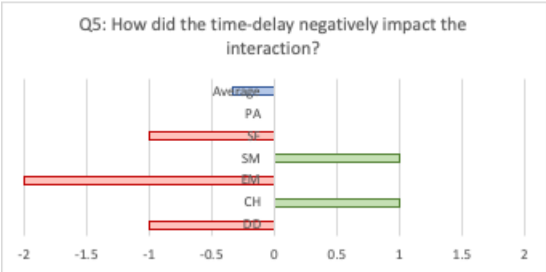


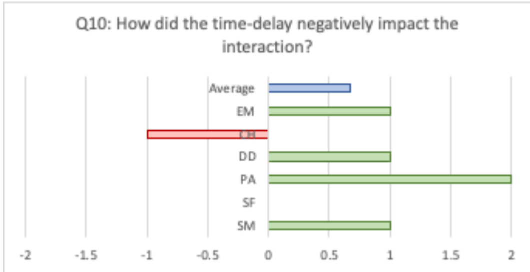


Impact of latency

After being in the role of the clinician, participants were asked: 'How did the time-delay negatively impact the interaction?' (Q5). Their responses were along a bipolar scale between 'no negative impact' at one end to 'extremely negative' at the other. After being in the role of the patient, the participants were asked the same question (Q10) with the same bipolar scale for their responses.

Five out of six participants reported a moderate directionality towards the negative pole, indicating a negative impact, when in the clinician role. This was reversed, with five out of six participants reporting a moderate directionality towards the positive pole, when they were in the patient role

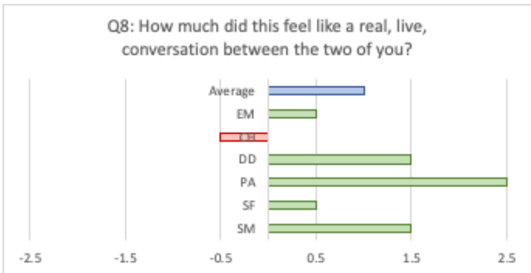




High-latency synchrony

After being in the role of the clinician, participants were asked: 'How much did this feel like a real, live, conversation between the two of you?' (Q8). Their responses were along a bipolar scale between 'not at all' at one end to 'very much' at the other.

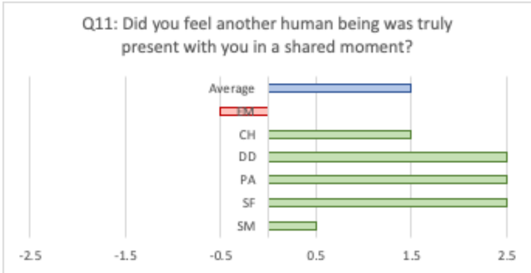
Five out of six reported a strong directionality towards the positive pole, indicating the experience of being in a real-time synchronous dialogue despite the five-minute one-way signal latency.



Co-presence

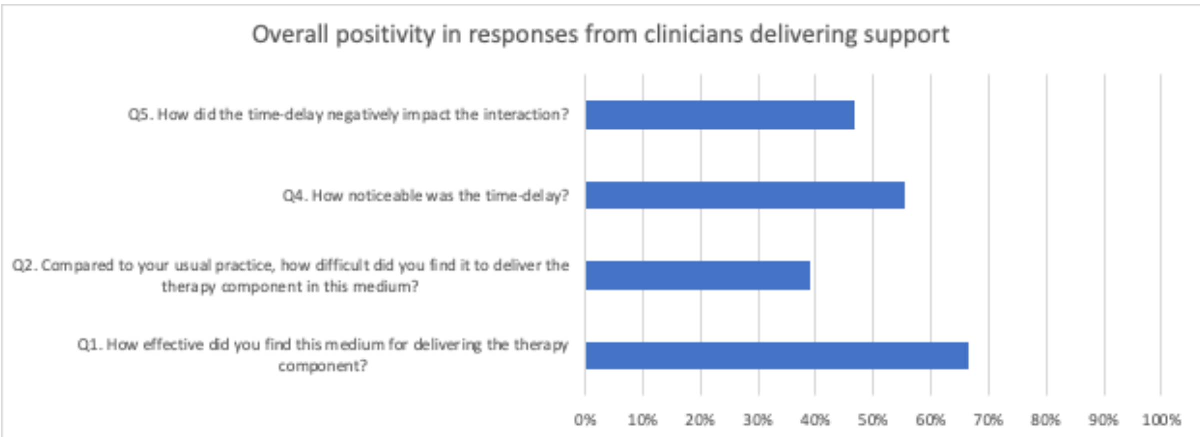
After being in the role of the patient, participants were asked: 'Did you feel another human being was truly present with you in a shared moment?' (Q11). Their responses were along a bipolar scale between 'yes, completely' at one end to 'not at all' at the other.

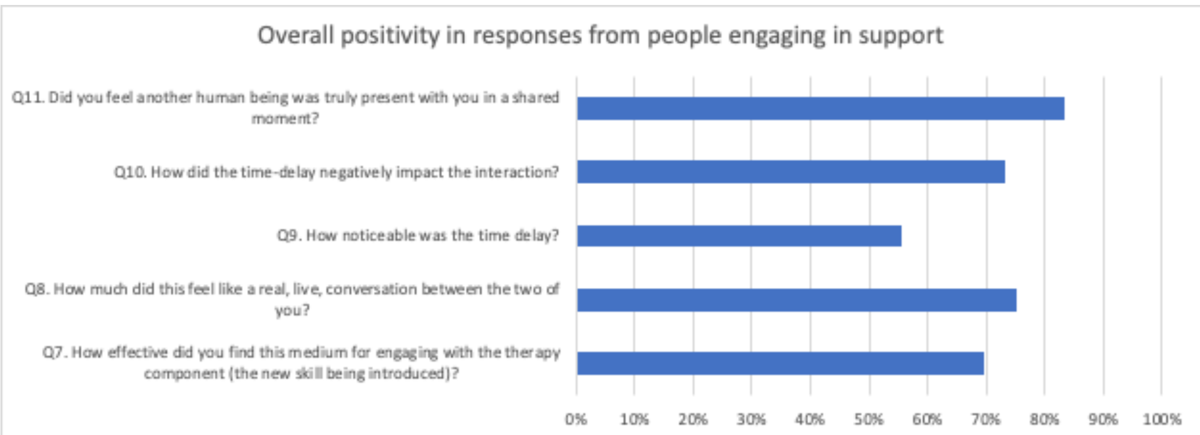
Five out of six participants reported a very strong directionality towards the positive pole, indicating the experience of co-presence, despite the five-minute one-way signal latency.



Summary

From the patient’s perspective, the experience reported was positive across all domains. This was also the case for the clinicians delivering support indicating they could deliver evidence-based therapy, but it was more difficult under these conditions compared to their day-to-day clinical practice. In contrast to their session partners, participants in the role of the clinician delivering support described the signal latency to be more noticeable and impactful. Taken together, the participants reported that it is feasible to deliver live, synchronous, sessions of psychological therapies under conditions of major signal latency when Space Braiding is the communication medium.





B4. Discussion

Synchronous psychological support is feasible

Interpersonal synchrony is defined as a shared focus of attention and behaviour that is coordinated by a shared rhythm and maintained through a period of time (Chetouani et al., 2017). Synchrony in a communication channel is required for the people communicating with one another to experience co-presence; the experience of being psychologically connected to another person in a shared present moment, even if that other person is not physically proximal (Oh et al, 2018). Overall, participants in both roles reported that it is feasible for synchronous sessions of psychological support to be delivered and engaged in under conditions of high latency using Space Braiding.

Several underlying features are of interest. Firstly, the two participants who gave a low rating for ineffectiveness were in pairs where the participant in the role of the clinician providing psychological support gave high ratings for difficulty and adaptation (described below). In other words, within a live session of psychological support, it is likely that a clinician who is struggling with the medium of communication (under conditions of signal latency) will have a negative impact on the experience of the person engaging with them in that session. This highlights the importance of clinical training for competency to optimise the experience of people engaging in support. It is also reasonable to consider that a patient perceiving the support they are receiving to be ineffective could require the clinician to work harder to deliver the agreed intervention.

Secondly, the total positive scoring for effectiveness in the clinician's role (Q1) was twice as high for participants when they took on that role in the second round of live psychological therapy sessions compared to how participants scored for effectiveness in the role of clinician in the first round. It is reasonable to suggest this represents an increase in competence and confidence from increased exposure to the communication medium and is therefore connected to the participant's capacity for rapid learning and adaptation. In order to design appropriate training protocols, it should be investigated how ratings of effectiveness change, in this context, as people accrue an increasing number of sessions using the Space Braiding communication tool.

This phenomenon was mirrored in the responses for difficulty in delivering the component of therapy (Q2), most likely representing a learning effect whereby participants who were in the role of the person engaging with support in the first round of sessions had that opportunity to experience Space Braiding. Unlike the participants who stepped into the clinician's role right away, they had time to contemplate how best to approach the role of the clinician providing support when the roles were switched in the second round of sessions that immediately followed.

To mitigate the learning effect, it is reasonable to suggest the following combination: one hour of training, one thirty-minute practice session, one sixty-minute practice session, and four real therapy sessions. While such a clinician would still be developing mastery, it is reasonable to expect them to have become broadly competent and dextrous with the tool by that point. Of course, in a real long duration mission, latency will be changing, not fixed. The possibility that different competencies apply to delivering effective psychological support across a large range of latencies should be investigated.

In contrast, the participants' reports of the degree to which latency was noticeable and problematic remained stable across the first and second round of communication sessions. It is reasonable to interpret that the capacity of Space Braiding to mitigate the perception and impact of latency may be immediately and sustainably facilitated for all users from first use but this should be subject to further investigation.

Where signal latency did separate the group was in the more negative responses of participants in the role of the clinician reporting the latency to be more noticeable and having an increased negative impact, compared to the reports from participants in the non-clinician role. One conjecture is that latency may collide with the features of some highly-protocolised therapeutic procedures that demand a linear sequencing. A number of contemporary approaches (e.g., process-focused psychotherapies) are arranged in flexible non-linear treatment structures that could transcend this issue if it proves to be an obstacle in high-latency contexts. Because of this, there is likely to be differing degrees of congruence between the most established evidence-based psychological therapies and (1) the affordances and constraints of the communication channels - synchronous and asynchronous - in deep space exploration and (2) the target population - the crew - and the uniqueness and complexity of the context they operate within. Even with the most congruent approaches identified, which is no small task, it is reasonable to imagine a further range of mediating and moderating factors that enable psychological therapists to optimally adapt to competently and confidently deliver these therapeutic collaborations under conditions of very high-latency.

Despite these challenges for the psychological therapists, in this study they did not impinge at all on the perceived effectiveness of the therapeutic component they were providing from the point of view of the person engaging in the support. That the impact of latency can be felt so acutely by psychological therapists while, simultaneously, not be felt by the people they are supporting in a live session, is a phenomenon also requiring further investigation to understand the mediating and moderating factors.

Synchrony and co-presence are produced

The questionnaire completed by participants also captured their experiences of communication synchrony and co-presence. Synchrony in a communication channel is not defined by the presence or absence of latency, although it is easier to achieve in a low-latency environment. Instead, communication synchrony is defined by a medium that enables interlocutors to have a shared focus of attention and behaviour, coordinated by a shared rhythm and maintained through a period of time (Chetouani et al., 2017). Synchrony in a communication channel is required for the emergence of co-presence between the interlocutors - the experience of being psychologically connected to another person in a shared present moment, even if that other person is not physically proximal (Oh et al, 2018). Co-presence is an important phenomenon in human computer-mediated communication such as Space Braiding. To describe an example closer to home, it is what enables a scientist overwintering at Concordia to enter into a satellite phone call with their closest friend on the other side of the planet and have their body respond with affiliative neurobiological changes in a comparable manner to when they are physically proximal and co-located.

In some instances, the participant in the role of the clinician delivering support reported negative directionality along dimensions of difficulty, difference and ineffectiveness. Even then, however, the positive directionality towards synchrony and co-presence for the participants in the role of the person engaging in support was maintained for the whole group in all but one instance. Based on review of the literature, it is possible this is the first research data describing the experience of high-latency synchrony and co-presence. As outlined in the context section above, interpersonal synchrony is a fundamental requirement in supporting crew health through affiliative interactions between crew and their closest friends and family and supporting health through the provision of live sessions of psychological support from the ground.

The above cannot be enabled without co-presence and, therefore, cannot be achieved a-synchronously. Human nervous systems co-regulate; one person's autonomic nervous system sensitively interacts with another person's autonomic nervous system in a way that facilitates greater emotional balance and physical health. Co-regulation occurs when people with close affiliative bonds experience co-presence, even if they are physically separated by very large distances. This is because cues of co-presence (within interactions enabled by computer-mediated communication over distance) activate affiliative mental representations that elicit the emotional connection and psychological closeness of the bond originally established by physical proximity (Tong & Walther, 2011).

The interpersonal synchrony at the heart of co-presence is observed in most social species (Xuan & Filkov, 2013), is central to the development and maintenance of affiliative bonds in mammals (Atzil et al., 2014). As a corollary of the psychological and physiological regulation described, synchrony produces a range of significant interpersonal social outcomes for humans. Of greatest significance, synchrony causes concepts of the self and other to merge (Rennung & Göritz, 2016) enabling closeness (Catmur & Heyes, 2013), affiliation (Hove & Risen, 2009), compassion (Valdesolo & DeSteno, 2011) and cooperation (Reddish, Fischer & Bulbulia, 2013). Qualities of utmost importance to the optimal cohesion, cooperation and performance of a crew in an exploration class mission.

In Q3 we asked participants in the clinician’s role to consider how different (as opposed to how difficult in Q2) it felt using Space Braiding under conditions of latency compared to their normal practice. Based on the responses, it was apparent that the positive and negative dimensions of the scale were not simple and did not generate responses amenable to straightforward interpretation. For example, it appears inevitable that a therapist would find the mode of communication different but that doesn't necessarily mean, when they report it, that they attach a negative orientation to that. Difference can also be stimulating and open new possibilities. Indeed, the group as a whole gave a very strong signal that Space Braiding offered new opportunities for doing psychological therapies, terrestrially (Q6; the data was not connected to spaceflight so it is not included in the analysis above).

What was evident from the outcome data around the concept of difference in Q3 was that in the first round of sessions, two out of the three participants in the clinician’s role reported scores towards the ‘very different’ end of the scale whereas in the second round of sessions, only one out of the three did. It is reasonable to imagine that for a psychological therapist delivering their most familiar components of therapy, the initial novelty of Space Braiding and the high-latency synchrony it enables may wear off as clinicians quickly adapt to the new communication medium to achieve long-established therapeutic objectives. Further work is required to investigate the degree to which a strong report from a clinician of ‘very different’, such as above, is being driven by the experience of high-latency synchrony or the resulting nonlinear method of delivering high-intensity therapy it enables.

The impact of isolation can be reduced

As well as presenting a challenge for crew to engage in synchronous psychological support with a clinician on the ground, latency also makes it hard for crew to engage in synchronous affiliative dialogue with the people they care most about - their closest friends and family (F&F). The impact of latency on interactions with F&F has yet to be fully investigated even though these communications will serve multiple purposes of providing social stimulation, mitigating the impact of chronic isolation and maintaining the affiliative bonds between crew and the people they care about the most. The quality of interactions with F&F, particularly the absence of sharing what is personal and private, the absence of intimacy, underpins the experience of loneliness for crew in analogue spaceflight research (Basner et al. 2014) and armed forces personnel in comparably isolated, confined and extreme environments (Carter & Renshaw, 2015). Human neurobiology, even in the case of extremely healthy well-trained astronauts, has evolved to expect affiliation, to grow and heal in its presence and to descend into dysregulation in its absence (Mikulincer & Shaver, 2007, Cacioppo & Patrick, 2008).

Not all social interactions are the same. A poverty of social stimulation, particularly that characterised by love and affiliation, is a major risk factor for behavioural and physical health problems (BMed 106, NASA, 2022) including depression, anxiety, aggression, impulsivity, sleep disturbance, cognitive impairment, (Cacioppo et al., 2014b) and an increased risk of cardiovascular and inflammatory disease (Hawkley & Cacioppo 2010). The relationships between crew members are significantly different to those between individual crew and their closest family and friends. Intimate interactions between people who are personally very *close*, especially one person disclosing personal feelings and the other providing understanding and reassurance (Ryff & Singer, 2000), supports autonomic regulation while enhancing long-term immune function and improving physical and mental health more broadly (Pennebaker, 1999). The brain's fear systems are calmed, and the social engagement and reward systems are stimulated (Cozolino, 2006, Cacioppo et al., 2014a).

These neurobiological changes are crucial to the optimal social functioning and performance of the crew but do not arise from the interactions *between* crew members (unless pairs with attachment bonds have been deliberately selected as crew), they are elicited from synchronous, affiliative, interactions between crew and their *closest* family and friends. It is reasonable to conceive, therefore, that the role of Space Braiding may not only be to improve operational and clinical support from the ground but to facilitate interactions between crew and those they share attachment bonds with to optimise health and prevent the onset of health problems driven by isolation.

B5. Conclusion

The outcome data gives a preliminary positive signal that it is feasible to deliver synchronous sessions of psychological therapies between clinicians on the ground and crew under conditions of Mars mission sized signal latencies.

While psychological therapists will exert effort to adapt to the high-latency context, the data indicates this does not negatively impact the experience of the people engaging with that psychological support and both parties report effectiveness. It should be highlighted that the clinicians in this initial pilot cohort had only a brief exposure to Space Braiding consisting of a short 10-min practice followed by two 60-min clinical role-play sessions and there was some evidence of a learning effect. Follow-on research can delineate the adaptation process clinician's will transition through from beginner to expert user status.

There is a superficial logic to the idea of selecting astronauts with the lowest sensitivity to the absence of affiliative neurobiological stimulation but the very psychological and physiological features that enable low sensitivity bring with them a similarly low capacity for detecting, attending to and appropriately supporting the psychological needs of self and others (Cacioppo & Patrick, 2008). A high-performing crew in a long-duration mission will require a group of individuals to have optimal capacities in common, not marked deficits. It is imperative that a mechanism is found to provide such a crew with a degree of the synchronous, affiliative, stimulation that their bodies are evolved to expect and, as the poverty of stimulation will inevitably be felt by psychologically healthy crew, enable effective psychological support to mitigate the harm.

Recommendations

Based on this initial study, the recommendations for further research are:

- Repeat the study in a larger population to confirm the preliminary findings.
- Investigate the feasibility of delivering different types of evidence-based psychological therapies through Space Braiding to understand which are the best match for that communication channel.
- Investigate the impact of dynamic latency across a mission profile. Remote, laboratory and analogue settings would be possible with a focus both on the impact of changing latency on communication effectiveness while also attending to the question of whether clinicians need to adopt different clinical strategies when operating at different latencies.

Additionally, in line with general progress in mental health knowledge and practice, reflected in the BMed gaps previously referenced, it would be advantageous for future research to adopt a health promotion approach. To focus on identifying what training and support combines to produce the best state of mental health possible under the conditions of a long duration mission. Such an approach assumes the notable mental fitness of astronauts and focuses on training, like physical exercise, to keep that fitness optimised under challenging conditions. Mental fitness is a capacity that can be depleted and renewed. Contemporary psychological therapies are well-placed to assist high-performing healthy individuals in that process of understanding what causes the depletion and strategically using cognitive and behavioural skills to drive renewal and maintain fitness.

To understand the key ingredients of that psychological training and support, further work is required to establish the relationship between the high-intensity psychological therapies support potentially possible through Space Braiding (ground to vehicle) and the low-intensity psychological therapies support readily available through a range of digital self-help products (onboard the vehicle). Guidance will need to be established so that the protocol-user can select the right type of support for a given situation.

This work could start with an investigation in an astronaut-like population by delivering psychological support for an overwintering crew in Antarctica with a time delay applied to all communication in and out of the station.. This study may have two experimental groups, one using Space Braiding with a large time delay to access psychological support, the other engaging in communication sessions of the same length with their closest family and friends, and a control group who participates in neither. Robust mental health screening tools would generate outcome data to compare the relative health outcome effect of psychological support versus social support versus current practice in a high-fidelity analogue context and population under conditions of large signal latencies.

The prime objective going forward is, therefore, to understand what evidence-based psychological therapies can (1) work effectively through the available channels of communication that are also (2) appropriate for the challenges of the unique context and crew of a long duration exploration mission.

Appendix I

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Appendix II

LATENCY

This appendix provides further details of the latencies that will be experienced on future Lunar or Martian mission

Latency for Lunar missions

At the Moon the latency caused by physics / distance is 1.3 seconds one way, so 2.6 seconds for a return message. This doesn't change because the moon goes around the Earth in an orbit that is almost a perfect circle so the distance is always roughly the same. The actual latency experienced by two people communicating between the Earth and the Moon during Artemis will be higher because we will be using "modern, digital, communication technology."

Digital communication does have advantages over "old-fashioned" analogue comms. The main ones being that it is less susceptible to interference and can also support higher bandwidth allowing for the transmission of more data overall.

However, digital communication does also have disadvantages, the most significant of these being additional delay. Speech is an analogue pressure wave in the air - ie a pressure wave of continuously variable amplitude. To digitise this the signal is 'sampled' and the amplitude mapped to one of a large number of discrete amplitudes. The digital signal is therefore an approximation of the analogue signal. The number of discrete amplitudes available needs to be large and the sampling needs to happen often in order for the digital signal to be a good enough approximation of the analogue. In a normal telephone call the signal is sampled 8,000 times every second. That is about the lowest sampling frequency you can use and still have a recognisable speech pattern. Other systems use higher frequency of sampling to get better quality. For example digital radio typically uses 44,000 samples per second.

On top of the sampling there are then other signal processing steps to apply, such as adding error correction codes (so, at the far end, the system can identify if a particular bit has been corrupted and then discard it) and then it is further processed into a string of 1s and 0s for actual transmission. At the other end the digitised signal is then used to recreate the digitised sound wave, the error correction information is used to discard any 'bad data' and then the clean digital signal is used to create an analogue pressure wave that is a pretty good approximation of the original speech.

The sampling, processing and "de-processing" steps all take time which generates a delay. There are also additional complexities including traffic prioritisation and packet routing which potentially introduce additional delay plus the fact that error correction processes will need to be reengineered as those currently deployed terrestrially will not work over the Delay Tolerant Networking protocol required for Artemis. Based on the authors engagement with contacts across ESA and NASA work in this area is still ongoing and the actual latency is not yet known. It is currently expected that the delay caused by signal processing will be the largest contribution to latency at the Moon.

None of this is required in analogue comms - the pressure wave simply directly creates a continuously varying electrical signal at one end and the reverse at the other. Hence Apollo only experienced the 1.3 seconds one way latency caused by distance.

Latency for Martian missions

For future Martian missions the delay caused by physics / distance will be much larger than at the Moon and so will be the dominant factor even though there will also be delays caused by signal processing.

The distance between the Earth and Mars varies continuously as the two planets follow their respective orbits around the Sun. We stated in the main body of the report that "the shortest possible latency to the Martian surface is about 3½ minutes one-way, the maximum is over 22 minutes" both of these were approximations as explained here.

The Earth and Mars make a close approach to each other roughly once every 26 months. Both planets' orbits around the sun are elliptical rather than perfect circles and Mars' orbit is highly elliptical, so the separation at closest approach varies. The absolute minimum possible distance between Earth and Mars is 54.6m km. This would happen if a close approach between the planets were to occur at the moment that the Earth is at aphelion (furthest from the sun in its orbit) and Mars is at perihelion (closest to the sun in its orbit). At that point the delay caused by distance in communication between the planets would be 3min01sec. The last time this happened was over 60,000 years ago.

The most recent 'really close approach' happened in 2003. At that point the delay was 3min06sec. The two planets won't come that close again for nearly 300 years.

At the time of writing the most recent close approach was on 30Nov22. That was an unusually distant close approach, over 80m km and the delay was 4m30sec. The most distant close approach, if Mars is at aphelion and Earth at perihelion, would be over 100m km, a delay of 5m 36s.

Similar variability applies to the maximum separation, hence our approximations used in the main text.

For each individual Martian mission a unique latency profile, similar to those shown on page 5, will need to be created.

Appendix III

Space Braiding: A tool for synchronous human communication under high-latency
Braiding divides a conversation into several threads, or Braids, and presents these to participants on a revolving carousel. At any one point in time the participant at one end of the latency, say on Mars or in transit to Mars, is reading and typing in one Braid whilst the other participant, on Earth, is reading and typing in the Braid on the opposite side of the carousel. Meanwhile content from the other, currently inactive, Braids is making its way across the void. By carefully controlling the number of Braids and the rotational speed, each participant will receive content from the other just as the carousel rotates so they are never exposed to the latency

The Braiding tool is designed for use in Earth based experiments, such as this one, and therefore the latency can be varied from session to session as can the number of Braids and other parameters. In this study those variables were all fixed across the entire experiment. Braiding maintains the sequence and theme of related utterances under time delay, removing the need for the participants to separately identify the linkages and untangle the themes.

Additionally, because braiding orchestrates both users' attention and behaviour to the same rhythm, it achieves interpersonal synchrony that is detectable by the users (they can tell they are in a shared moment of live conversation). Although not the subject of this study it is anticipated that this synchrony will be beneficial in maintaining the psychological health of future crew by enabling meaningful communication with their loved ones on Earth. Interpersonal synchrony may also prove to aid more effective operational communication in specific use cases.

A US patent has been awarded for Space Braiding. Number 11,397,521.

Appendix IV

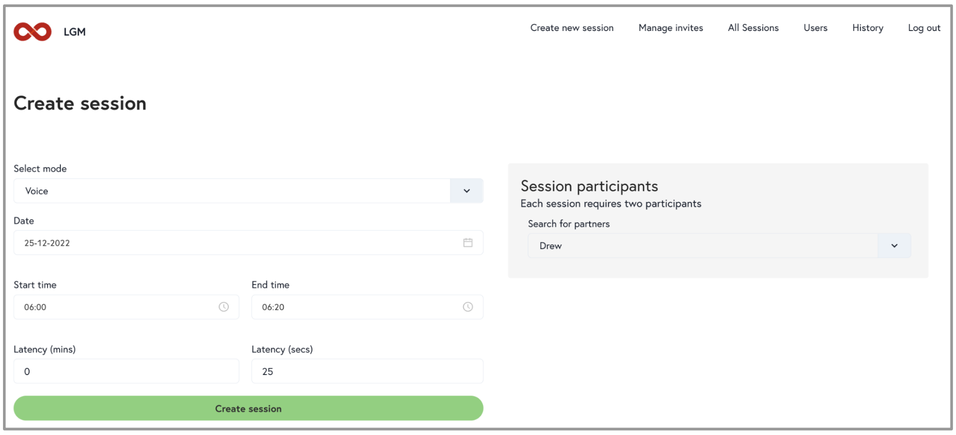
Latency Governed Voice

Latency Governed Voice (LGV) is a tool that Braided Communications designed and built specifically to test the impact of latency on voice communication.

It is designed to allow two participants to communicate with each other as if they were having a traditional voice telephone conversation but separated by such great distance that there is a noticeable latency.

To use LGV participants need an LGV account, associated with their email. They log in and schedule sessions ahead of time (you can't just place a telephone call to someone if they are several light minutes away as it will take several minutes before the signal reaches them and their phone rings!). Their chosen communication partner receives an email notification that they have been invited to an LGV session and can choose to accept or decline.

As nowhere on Earth is far enough away from anywhere else to actually generate real distance induced latency the latency in LGV sessions can be selected by the session initiator and is generated at the server. The screenshot below shows an LGV session about to be set up for 6am on Christmas day with a latency of 25 seconds.

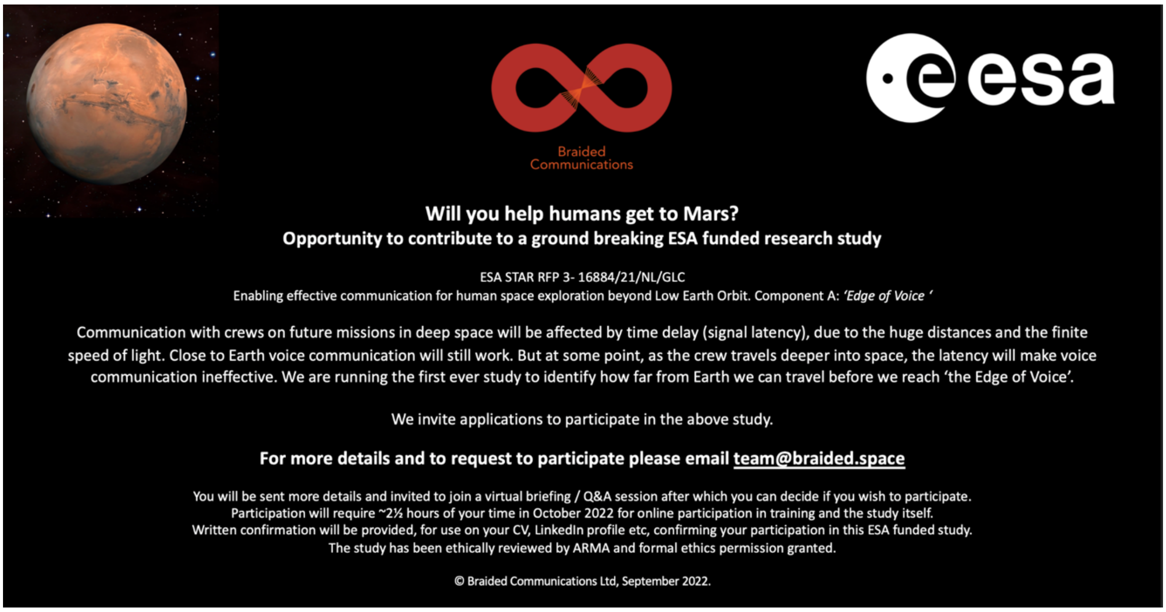


Assuming the session is accepted both participants log back in to LGV on their laptops shortly before the session is scheduled to start. The session starts automatically and each participant can speak as they wish (using wired headphones to prevent any feedback). Their partner hears everything they have said, but they do not hear it immediately, instead they hear it at a later time, based on the chosen latency.

In this study participants were allocated an account created with a dummy email address (such at *team+ostrich@braided.space*) and all LGV sessions were pre-scheduled and pre-accepted by a Braided employee, to eliminate any opportunity for error at that stage

Appendix V

Edge of Voice recruitment flyer



Appendix VI

Edge of Voice operational scenarios & emergency updates

A. *Lunar (Crew)*
B. *Lunar (Ground)*
C. *Houdini (Crew)*
D. *Houdini (Ground)*
E. *Emergency updates*

A. Lunar (Crew)

Evacuate Habitat "Station Lunar Frontier" – Information for the Crewmember

This is a fictional situation. You and your remote teammate are tasked with developing an evacuation plan for the situation described. You will be the crewmember in this situation; your remote teammate will act as mission support. ***The communication between you and your remote teammate will be delayed.***

Please address the topics specified below in your interaction with your remote teammate. We also provide you with relevant information in the Lunar Frontier Inventory that you may refer to and use in your decision making. We suggest you go over the information provided as a way of preparing for the discussion. You and your remote teammate are welcome to bring in your own ideas but do not include any real, personal, information from your own life. You have creative liberty to invent any new details you wish and please remember you are not being evaluated in any way on what you choose to say, or whether you did the task correctly. We will not evaluate your solutions; rather our research focus is on the communication medium, and the extent to which it supports, or fails to support, space-ground communication under time-delayed conditions.

Scenario Context

You and three crewmates have been living in Station Lunar Frontier on the surface of the Moon for the past three months conducting an array of research: in physiology (measure physiological changes in mice and medaka—a small fish); biomedicine (conduct molecular and genetic analysis of microorganisms), plant biology (develop and grow plants for bioregenerative food production); and radiation (test radiation protective materials). The mission has been going according to plan – until today.

Right before breakfast the system monitor program triggered the highest alarm. A steady CO_2 build up in Station Lunar Frontier is being observed. Indicators point to a malfunction in the life support system as the culprit. In conference with ground support, it is decided that you and your crewmates need to evacuate the station for the time being, until system engineers in MCC have determined the source of the malfunction and compiled repair procedures. The only option available to you is a deserted outpost habitat called Explorer that is 45 miles from Lunar Frontier and had been used in the past to house a crew of 2 for short-term geological research. Explorer was occupied last 14 months ago. Satellite and telemetry data indicate that Explorer's solar panels and habitat systems are all functioning. The available transfer vehicle supports a payload of 150 pounds in addition to the crew. The vehicle comes with its own power source, the latest version of a Multi- Mission

Radioisotope Thermoelectric Generator (MMRTG), that charges its two primary batteries and provides sufficient energy to travel 15 miles per hour with a payload of 100 pounds.

Goals for Upcoming Discussion with Mission Support

You and mission support need to plan your evacuation. Below is a list of action items that concern four critical issues you and mission support have identified. The critical issues are:

- Food & Fluids
- Health & Hygiene
- Equipment & Personal Effects to Take Along
- Preparing Lunar Frontier for Evacuation

What do you need to do and consider? What should you take with you? What are your preferences? What is necessary to survive? **You will need to share your preferences and rationale with mission support and identify and reconcile differences. Your goal is to come up with an action agenda that represents your shared priorities and perspectives across all four topics**.

TOPIC-1. Food & Fluids

- **What food should you take? Quantity** in terms of days *(Consult Station Inventory list to make your choices).*
- **Should you take plants or seeds?** Yes/no? Which ones? *(Consult Station Inventory list to make your choices)*

TOPIC-2. Health & Hygiene

- **Which medication will you need to pack? Prioritize the 10 most important medications**. *Antibiotic Ointment; Antibiotics; Antihistamines; Aspirin; Benadryl; Calcium; Eye Drops; Epsom Salt; Hand Sanitizer;Ibuprofen; Metamucil; Multi-Vitamins; Nasal Spray; Pain Medication; Rubbing Alcohol; Sleeping Pills; Vitamin D*
- **Which medical equipment? Prioritize the 10 most important medical equipment items.** *Band-Aids;Bandages; Blood Pressure Monitor; Blood Sugar Meter; Ear Wax Removal Kit; Gauze Pads; Heart Rate Monitor; Microscope*; *Ophthalmoscope*; *Pulse Oximeter; Rolled Gauze; Safety Pins; Syringe; Stethoscope*
- **Which items of personal hygiene should you take?** *Absorbent garments; Body lotion; Body wash; Facial crème; Hand soap; Laundry detergent; Makeup; Razor; Toilet paper; Tweezers; Urinary inserts*

TOPIC-3. Equipment and Personal Effects to Take Along

- **Which equipment/items do you need to take with you? Order the following items according to priority:** *Aquatic habitat*; *Compass;* Flashlight; *Mice habitat; Microscope*; *Multi-use tool; Laptops; Light bulbs; Mobile green house; Mobile freezer unit; Plant pillows for plant growth; Pillows; Radio antenna;* Re-chargeable lithium-ion batteries to enhance MMRTG; *Sleeping bags; Solar panels*; *Spade*; *Tarp*
- **Should you relocate science experiments?** Yes/no? Which ones?
- **Which entertainment & memorabilia should you take with you?** *Books; Console for computer games; Family presents; iPad; iPod; Laptop; Photos*

TOPIC-4. Preparing Lunar Frontier for Evacuation

- **Which, if any of the following items, do you need to secure/store?** *Blood samples; Cell samples; Computer workstations; Exercise equipment; Freezers; Food*; *Garbage;*

Medications; Microscopes; Plants; Refrigerator; Robotic arm; Stowage racks; *Waste management compartment; Water hoses*

- **Should you complete any science experiments prior to evacuation? Which ones?**
- **Which systems of Station Lunar Frontier should you power down?** (*Consult Station Inventory list to make your decision)*
- **Which station systems should you keep running on reduced power?** *(Consult Station Inventory list to make your decision)*

LUNAR FRONTIER INVENTORY

FOOD & BEVERAGES

	EXAMPLES
REFRIGERATED	
Dairy	Cheese, Yoghurt
Fruits	Apple, Grapefruit, Oranges
FROZEN	
Meals	Meat (beef/chicken/lamb/pork) dishes; Seafood; Egg-, Pasta- and Rice dishes; Pizza
Soups	Beef stew; Chicken noodle; Cream of Chicken/Mushroom/Broccoli
Fruits	Peaches; Blueberries; Banana
Grains	Breads; Rolls; Tortilla
Breakfast items	Cinnamon roll; Pancakes; Waffles
Starchy Vegetables	Potatoes (baked/oven fried/mashed); Corn; Squash corn casseroles
Vegetables	Asparagus; Beans; Broccoli
Desserts	Cakes; Ice cream; Frozen yoghurt
Pies and Pastry	Cheesecake; Apple/Pecan/Pumpkin pie
Beverages	Apple juice, Lemonade
Fruits	Peaches; Blueberries; Banana
Condiments	Margarine, Grated cheese
Hot Cereals	Oatmeal, Grits
THERMOSTABILIZED	
Fruit	Applesauce; Fruit cocktail
Salads	Chicken-, Bean-, Pasta salad
Soups	Chili; Vegetable
Desserts	Assorted puddings
Condiments	Assorted sauces and jams; Mayo; Mustard; Honey; Peanut Butter
Beverages	Milk; V-8; Fruit juices; Gatorade
NATURAL FORM	
Fruit	Assorted dried fruit; Trail mix
Grains	Assorted crackers
Desserts	Assorted cookies

Snacks	Beef jerky
Nuts	Almonds; Peanuts; Cashews
Candy	Candy-coated chocolates; Gum
REHYDRATABLE	
Beverages	Assorted coffees & teas, Instant breakfast drinks (chocolate, vanilla), Orange drink
IRRADIATED	
Meat	Beef steak, Smoked turkey
EVA FOOD	In-suit fruit bar

Plants and Seeds
Plants and seeds are available for the following:

Arugula	Collard Greens	Radishes
Basil	Dandelion	Red Romaine Lettuce
Beets	Endive	Spinach
Bok Choy	Iceberg Lettuce	Swiss Chard
Butter Lettuce	Kale	Tomatoes
Cabbage	Mizuna	Water Cress
Corn	Potato	Zinnia

Station Systems

Environmental Control and Life Support System (ECLSS)
ECLSS includes systems that provide the crew with a comfortable environment in which to live and work.

- Active thermal control system
- Cabin air revitalization
- Crew compartment cabin pressurization
- Supply and wastewater
- Wastewater tank
- Water collection system
- Water coolant loop system

Computers and Data Management System (CDMS)
The CDMS stores and transfers information essential to Station operations.

Electrical Power System (EPS)
The EPS generates, stores, and distributes power and converts and distributes secondary power within the station.

Therma Control System (TCS)
The TCS maintains station temperatures within defined limits.

Communications System (CS)
The CS allows the crew to talk to ground support centers and it enables ground support to monitor and maintain Station systems and send commands to these systems.

Crew Health Care System/Integrated Medical System (CHeCS)
The CHeCS is a suite of hardware on the station that provides the medical and environmental capabilities necessary to ensure the health and safety of crewmembers.

- Countermeasure systems – provides equipment and protocols for daily exercise regiments, monitors crew during exercise
- Environmental health system – monitors atmosphere for gaseous contaminants, microbial contaminants, water quality, and radiation levels
- Health maintenance system –provides inflight life support, medical care and health monitoring capabilities

Plant Habitat
The unit is a closed-loop system with a controlled environment to grow plants.

Microgravity Science Glovebox (MSG)
The MSG is similar to a ground-based laboratory and provides a safe and contained environment for the crew to conduct research with liquids, flames, and particles. A filtered air circulation system and airlock ensure containment of the research environment.

B. Lunar (Ground)

Evacuate Habitat "Station Lunar Frontier" – Information for Mission Support

This is a fictional situation. You and your remote teammate are tasked with developing an evacuation plan for the situation described. You will act as mission support in this situation; your remote teammate will be a space crewmember. The communication between you and your remote teammate will be delayed.

Please address the topics specified below in your interaction with your remote teammate. We also provide you with relevant information in the Lunar Frontier Inventory that you may refer to and use in your decision making. We suggest you go over the information provided as a way of preparing for the discussion. You and your remote teammate are welcome to bring in your own ideas but do not include any real, personal, information from your own life. You have creative liberty to invent any new details you wish and please remember you are not being evaluated in any way on what you choose to say, or whether you did the task correctly. We will not evaluate your solutions; rather our research focus is on the communication medium, and the extent to which it supports, or fails to support, space-ground communication under time-delayed conditions.

Scenario Context
A crew of four astronauts have been living in Station Lunar Frontier on the surface of the Moon for the past three months conducting an array of research: in physiology (measure physiological changes in mice and medaka—a small fish); biomedicine (conduct molecular and genetic analysis of

microorganisms), plant biology (develop and grow plants for bioregenerative food production); and radiation (test radiation protective materials). The mission has been going according to plan – until today.

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Goals for Upcoming Discussion with the Crew
You and the crew need to plan the crew's evacuation. Below is a list of action items that concern four critical issues you and the crew have identified. The critical issues are:

- Food & Fluids
- Health & Hygiene
- Equipment & Personal Effects to Take Along
- Preparing Red Frontier for Evacuation

What should the crew do and consider? What should they take with them? What are your preferences? What is necessary for the crew to survive? You will need to share your preferences and rationale with the crew and identify and reconcile differences. Your goal is to come up with an action agenda that represents your shared priorities and perspectives across all four topics.

TOPIC-1. Food & Fluids

- What food should the crew take? Quantity in terms of days (Consult Station Inventory list to make your choices).
- Should they take plants or seeds? Yes/no? Which ones? (Consult Station Inventory list to make your choices)

TOPIC-2. Health & Hygiene

- Which medication should the crew pack? Prioritize the 10 most important medications. Antibiotic Ointment; Antibiotics; Antihistamines; Aspirin; Benadryl; Calcium; Eye Drops; Epsom Salt; Hand Sanitizer;Ibuprofen; Metamucil; Multi-Vitamins; Nasal Spray; Pain Medication; Rubbing Alcohol; Sleeping Pills; Vitamin D
- Which medical equipment? Prioritize the 10 most important medical equipment items. Band-Aids;Bandages; Blood Pressure Monitor; Blood Sugar Meter; Ear Wax Removal Kit; Gauze Pads;

Heart Rate Monitor; Microscope; Ophthalmoscope; Pulse Oximeter; Rolled Gauze; Safety Pins; Syringe; Stethoscope

- Which items of personal hygiene should the crew take? Absorbent garments; Body lotion; Body wash; Facial crème; Hand soap; Laundry detergent; Makeup; Razor; Toilet paper; Tweezers; Urinary inserts

TOPIC-3. Equipment and Personal Effects to Take Along

- Which equipment/items should the crew take with them? Order the following items according to priority: Aquatic habitat; Compass; Flashlight; Mice habitat; Microscope; Multi-use tool; Laptops; Light bulbs; Mobile green house; Mobile freezer unit; Plant pillows for plant growth; Pillows; Radio antenna; Re-chargeable lithium-ion batteries to enhance MMRTG; Sleeping bags; Solar panels; Spade; Tarp
- Should they relocate science experiments? Yes/no? Which ones?
- Which entertainment & memorabilia should they take along? Books; Console for computer games; Family presents; iPad; iPod; Laptop; Photos

TOPIC-4. Preparing Lunar Frontier for Evacuation

- Which, if any of the following items, do they need to secure/store? Blood samples; Cell samples; Computer workstations; Exercise equipment; Freezers; Food; Garbage; Medications; Microscopes; Plants; Refrigerator; Robotic arm; Stowage racks; Waste management compartment; Water hoses
- Should they complete any science experiments prior to evacuation? Which ones?
- Which systems of Station Lunar Frontier should they power down? (Consult Station Inventory list to make your decision)
- Which station systems should they keep running on reduced power? (Consult Station Inventory list to make your decision)

LUNAR FRONTIER INVENTORY

FOOD & BEVERAGES

	EXAMPLES
REFRIGERATED	
Dairy	Cheese, Yoghurt
Fruits	Apple, Grapefruit, Oranges
FROZEN	
Meals	Meat (beef/chicken/lamb/pork) dishes; Seafood; Egg-, Pasta- and Rice dishes; Pizza
Soups	Beef stew; Chicken noodle; Cream of Chicken/Mushroom/Broccoli
Fruits	Peaches; Blueberries; Banana
Grains	Breads; Rolls; Tortilla
Breakfast items	Cinnamon roll; Pancakes; Waffles
Starchy Vegetables	Potatoes (baked/oven fried/mashed); Corn; Squash corn casseroles

Vegetables	Asparagus; Beans; Broccoli
Desserts	Cakes; Ice cream; Frozen yoghurt
Pies and Pastry	Cheesecake; Apple/Pecan/Pumpkin pie
Beverages	Apple juice, Lemonade
Fruits	Peaches; Blueberries; Banana
Condiments	Margarine, Grated cheese
Hot Cereals	Oatmeal, Grits
THERMOSTABILIZED	
Fruit	Applesauce; Fruit cocktail
Salads	Chicken-, Bean-, Pasta salad
Soups	Chili; Vegetable
Desserts	Assorted puddings
Condiments	Assorted sauces and jams; Mayo; Mustard; Honey; Peanut Butter
Beverages	Milk; V-8; Fruit juices; Gatorade
NATURAL FORM	
Fruit	Assorted dried fruit; Trail mix
Grains	Assorted crackers
Desserts	Assorted cookies
Snacks	Beef jerky
Nuts	Almonds; Peanuts; Cashews
Candy	Candy-coated chocolates; Gum
REHYDRATABLE	
Beverages	Assorted coffees & teas, Instant breakfast drinks (chocolate, vanilla), Orange drink
IRRADIATED	
Meat	Beef steak, Smoked turkey
EVA FOOD	In-suit fruit bar

Plants and Seeds

Plants and seeds are available for the following:

Arugula	Collard Greens	Radishes
Basil	Dandelion	Red Romaine Lettuce
Beets	Endive	Spinach
Bok Choy	Iceberg Lettuce	Swiss Chard
Butter Lettuce	Kale	Tomatoes
Cabbage	Mizuna	Water Cress
Corn	Potato	Zinnia

Station Systems

Environmental Control and Life Support System (ECLSS)
ECLSS includes systems that provide the crew with a comfortable environment in which to live and work.

- Active thermal control system
- Cabin air revitalization
- Crew compartment cabin pressurization
- Supply and wastewater
- Wastewater tank
- Water collection system
- Water coolant loop system

Computers and Data Management System (CDMS)
The CDMS stores and transfers information essential to Station operations.

Electrical Power System (EPS)
The EPS generates, stores, and distributes power and converts and distributes secondary power within the station.

Therma Control System (TCS)
The TCS maintains station temperatures within defined limits.

Communications System (CS)
The CS allows the crew to talk to ground support centers and it enables ground support to monitor and maintain Station systems and send commands to these systems.

Crew Health Care System/Integrated Medical System (CHeCS)
The CHeCS is a suite of hardware on the station that provides the medical and environmental capabilities necessary to ensure the health and safety of crewmembers.

- Countermeasure systems – provides equipment and protocols for daily exercise regiments, monitors crew during exercise
- Environmental health system – monitors atmosphere for gaseous contaminants, microbial contaminants, water quality, and radiation levels
- Health maintenance system –provides inflight life support, medical care and health monitoring capabilities

Plant Habitat
The unit is a closed-loop system with a controlled environment to grow plants.

Microgravity Science Glovebox (MSG)
The MSG is similar to a ground-based laboratory and provides a safe and contained environment for the crew to conduct research with liquids, flames, and particles. A filtered air circulation system and airlock ensure containment of the research environment.

C. Houdini (Crew)

Surviving on Houdini – Information for the Crewmember

This is a fictional situation. You and your remote teammate are tasked with developing a survival plan for the situation described. You will be the crewmember in this situation; your remote teammate will act as mission support. The communication between you and your remote teammate will be delayed.

Please address the topics specified below in your interaction with your remote teammate. We suggest you go over the information provided as a way of preparing for the discussion. You and your remote teammate are welcome to bring in your own ideas but do not include any real, personal, information from your own life. You have creative liberty to invent any new details you wish and please remember you are not being evaluated in any way on what you choose to say, or whether you did the task correctly. We will not evaluate your solutions; rather our research focus is on the communication medium, and the extent to which it supports, or fails to support, space-ground communication under time-delayed conditions.

Scenario Context

You are a member of a 4-person space crew originally scheduled to dock with and deliver resupply to the base station on the surface of Houdini, a recently discovered asteroid. However, due to mechanical difficulties, your ship was forced to land at a spot some 30 miles from the station. During reentry and landing, much of the equipment aboard was damaged and, since survival depends on reaching the base station, the most critical items available must be chosen for the 30-mile trip. It is estimated that you can walk on the surface of Houdini with a maximum speed of 3 miles/hour.

Goals for Your Discussion with Mission Support

Luckily, you are able to communicate with mission support on Earth and coordinate with them. Your task is to decide jointly with mission support which items you should take with you on your journey. You have provided mission support with a list of items left intact and undamaged after landing. Items fall into four categories:

- Food
- Fluids
- Medication
- Equipment & Tools

Which are the most important items in each category? Select up to 4 items per category and where applicable, specify the quantity per item. You will need to share your preferences and rationale with mission support and identify and reconcile differences. Your goal is to come up with a list of items that represents your shared priorities and perspectives across all four categories.

CATEGORY-1. Food
7 Trail mix
5 packages of irradiated turkey
20 in-suit fruit bars
4 bags of applesauce (thermostabilized)
16 containers of chocolate and vanilla puddings
8 bags of catsup

10 cups of assorted jelly (thermostabilized)
6 containers of thermostabilized soups
6 packages of gum
9 containers of assorted puddings (chocolate, vanilla, lemon)

CATEGORY-2. Fluids
10 gallons of water
One case of dehydrated milk
15 packs orange drinks (rehydratable)
12 containers of instant breakfast drinks (assorted flavors; rehydratable)
16 packages of rehydratable coffee
12 containers of V8 (thermostabilized)
6 containers of tomato juice (thermostabilized)
10 packages of soy sauce
8 containers of dehydrated chicken broth
7 containers of Gatorade (thermostabilized)

CATEGORY-3. Medication
First aid kit, including injection needle
Pain medication
Antibiotic ointment
Eye drops
Antibiotics
Rubbing alcohol pads
Rolled gauze bandages
Safety pins
Band aids
Adhesive tape

CATEGORY-4. Tools & Equipment
Signal flares
Flashlight
Sleeping bags
Parachute silk
Two 100 lb. tanks of oxygen
iPads
Mortar & pestle
Rechargeable batteries
Tarp
Multi-use tool
Map of Houdini

D. Houdini (Ground)

Surviving on Houdini – Information for Mission Support

This is a fictional situation. You and your remote teammate are tasked with developing a survival plan for the situation described. You will be a member of mission support in this situation; your remote teammate will act as crew member. The communication between you and your remote teammate will be delayed.

Please address the topics specified below in your interaction with your remote teammate. We suggest you go over the information provided as a way of preparing for the discussion. You and your remote teammate are welcome to bring in your own ideas but do not include any real, personal, information from your own life. You have creative liberty to invent any new details you wish and please remember you are not being evaluated in any way on what you choose to say, or whether you did the task correctly. We will not evaluate your solutions; rather our research focus is on the communication medium, and the extent to which it supports, or fails to support, space-ground communication under time-delayed conditions.

Scenario Context

A 4-person space crew was scheduled to dock with and deliver resupply to the base station on the surface of Houdini, a recently discovered asteroid. However, due to mechanical difficulties, their ship was forced to land at a spot some 30 miles from the station. During reentry and landing, much of the equipment aboard was damaged and, since survival depends on reaching the base station, the most critical items available must be chosen for the 30-mile trip. It is estimated that the crew can walk on the surface of Houdini with a maximum speed of 3 miles/hour.

Goals for Your Discussion with the Crew

Luckily, you are able to communicate with the crew and coordinate with them. Your task is to decide jointly with the crew which items they should take on their journey. The crew have provided mission support with a list of items left intact and undamaged after landing. Items fall into four categories:

- Food
- Fluids
- Medication
- Equipment & Tools

Which are the most important items in each category? Select up to 4 items per category and where applicable, specify the quantity per item. You will need to share your preferences and rationale with mission support and identify and reconcile differences. Your goal is to come up with a list of items that represents your shared priorities and perspectives across all four categories.

CATEGORY-1. Food
7 Trail mix
5 packages of irradiated turkey
20 in-suit fruit bars
4 bags of applesauce (thermostabilized)
16 containers of chocolate and vanilla puddings
8 bags of catsup

10 cups of assorted jelly (thermostabilized)
6 containers of thermostabilized soups
6 packages of gum
9 containers of assorted puddings (chocolate, vanilla, lemon)

CATEGORY-2. Fluids
10 gallons of water
One case of dehydrated milk
15 packs orange drinks (rehydratable)
12 containers of instant breakfast drinks (assorted flavors; rehydratable)
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6 containers of tomato juice (thermostabilized)
10 packages of soy sauce
8 containers of dehydrated chicken broth
7 containers of Gatorade (thermostabilized)

CATEGORY-3. Medication
First aid kit, including injection needle
Pain medication
Antibiotic ointment
Eye drops
Antibiotics
Rubbing alcohol pads
Rolled gauze bandages
Safety pins
Band aids
Adhesive tape

CATEGORY-4. Tools & Equipment
Signal flares
Flashlight
Sleeping bags
Parachute silk
Two 100 lb. tanks of oxygen
iPads
Mortar & pestle
Rechargeable batteries
Tarp
Multi-use tool
Map of Houdini

E. Emergency updates

Scenario - HOUDINI

5 mins into the comms session
URGENT SITUATION UPDATE [HOUDINI, GROUND]
In mission control you have been told that an approaching solar flare has been detected. It will hit Houdini in 12-15 hours. The crew absolutely MUST reach the station by that time, it is the only place on Houdini with sufficient radiation shielding for the crew to survive. You need to tell the crew immediately and initiate planning.

10 mins into the comms session
URGENT SITUATION UPDATE [HOUDINI, CREW]
One of your crewmates who has been gathering supplies has fallen and twisted their ankle. It looks like they will still be able to walk, but more slowly, perhaps 2mph instead of 3 and will not be able to carry anything. You need to tell mission control immediately so planning adjustments can be made.

Scenario - LUNAR

5 mins into the comms session
URGENT SITUATION UPDATE [LUNAR, GROUND]
In mission control you realise the CO_2 build up is accelerating. The crew MUST be out of the habitat in less than 2 hours and the CO_2 levels will become fatal for the mice and fish. Those experiments require completion of the animal's life cycles in order to gather any useful data so the crew needs to prioritise taking these experiments if possible, to avoid having wasted all effort to date. You need to communicate this to the crew immediately.

10 mins into the comms session
URGENT SITUATION UPDATE [LUNAR, CREW]
Your crewmate has just informed you that one of the 2 batteries on the transfer vehicle appears to be faulty. It has zero charge and is not recharging. Your speed of travel will be reduced to 7.5mph and they do not know if the vehicle has sufficient oxygen for the extended transfer time. You need to communicate this to the ground immediately.

Appendix VII

Ethics approval final report

Study Title: Enabling effective communication for human space exploration beyond Low Earth Orbit

Organisation: Braided Communications Limited

Drew Smithsimmons

Co-founder & Director

drew@braided.space

Rob Brougham

Co-founder & Director

rob@braided.space

Documents Reviewed:
Study Protocol: ESA STAR RFP 3-16884/21/NL/GLC/ Enabling effective communication for human space exploration beyond Low Earth Orbit: v2 - June 2022

Edge of Voice - Flyer

Google forms - for data collection

Powerpoint slides for training sessions- for each of the two experiments

Ethics Reviewer: David Carpenter RMN, RGN, Dip N, Dip N Ed, BA Hons (Philosophy – London), MA Medical Ethics and Law (London). On behalf of ARMA

Brief overview of study: This study comprises two experiments in the form of simulations: Components A (with student participants) and B (with therapist participants). Both explore the impact of time delays in communication between earth and space. Braided has developed a tool known as *Space Braiding* to mitigate communication difficulties. The two experiments are designed to collect feedback from participants using the tool. According to the protocol:

Component A is an investigation into the impact of time delay (signal latency) upon the effectiveness of voice communication between a human crew and the ground in the initial phase of transit to Mars and the final phase of return. Component B is an investigation into the feasibility of delivering live sessions of psychological therapy for *those crew, with a psychological therapist on the ground, under conditions of very large signal latencies that will occur in the middle phases of transit and on Mars surface.*

Data will be collected on Google forms. The data will be confined to participants' experiences rather than the content of the communications. The overall aim is to test the feasibility of using the Braided tool rather than its efficacy.

Social or scientific value; scientific design and conduct of the study: The protocol was revised following my initial review, where I identified a few, largely methodological, issues- thank you.

This study has two components both comprising small-*n*, within-subjects, repeated measures, quasi-experimental designs. There are no ethics concerns with the overall conduct of the study or its design.

Recruitment arrangements: Recruitment will largely be via known connections - given the low risk status of the study and the ease with which participants can withdraw, I see no ethical concerns. A recruitment flyer is to be deployed: This is clearly set out and provides sufficient information to ensure informed consent. The PI has agreed to add one further bullet with regard to processing personal data. No further written information sheets or consent forms are required. Potential participants will have an opportunity to opt out of the study following the training sessions.

Favourable risk benefit ratio; anticipated benefits/risks for research participants (present and future): There are no significant risks entailed in participation. It is planned to retain recordings of the therapists participating in Component B - verbal consent can be used. There is clearly scientific value in these recordings; they will not include any personally identifiable information. Participants can opt out from this aspect without any penalty.

Care and protection of research participants; respect for potential and enrolled research participants' welfare & dignity: No concerns

Informed consent process and the adequacy and completeness of research participant information: Necessary and sufficient information is provided on the flyer and within the training sessions. I would suggest that consent is assumed but participants should be given an opportunity to opt out at the ends of the respective training sessions

Summary: I have no hesitation in giving a favourable ethics opinion.

David Carpenter

25th June 2022

Appendix VIII

Powerpoint slides for Edge of Voice training

"The Edge of Voice"

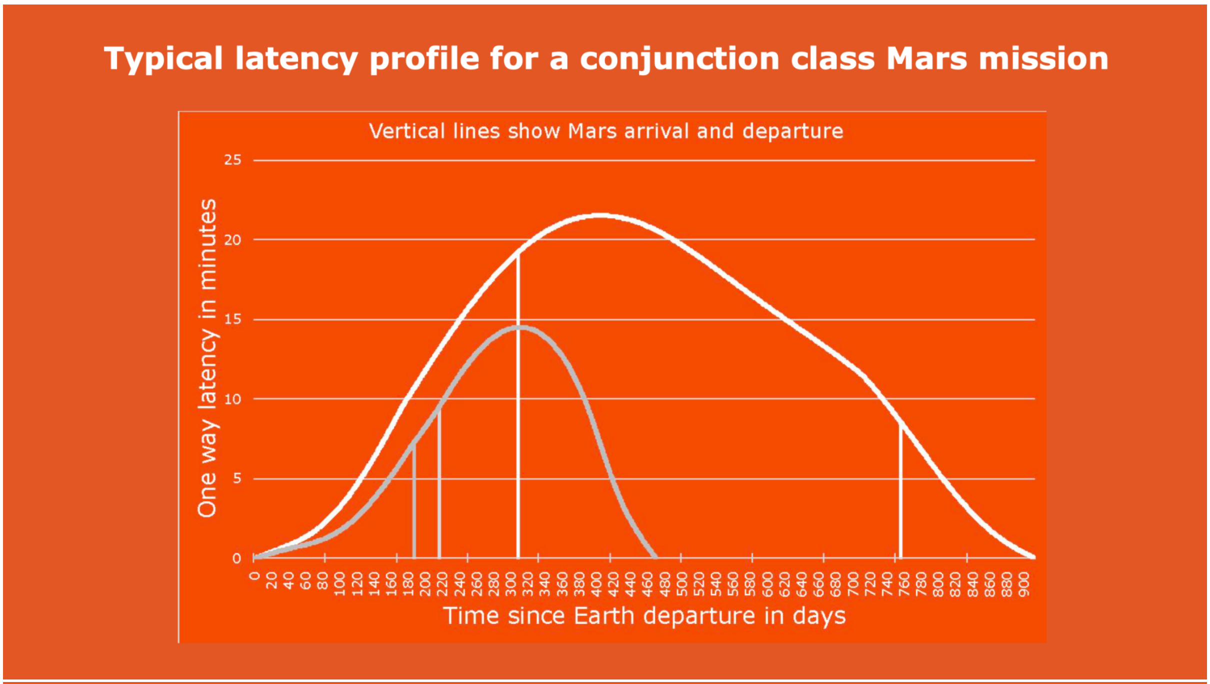
October 2022

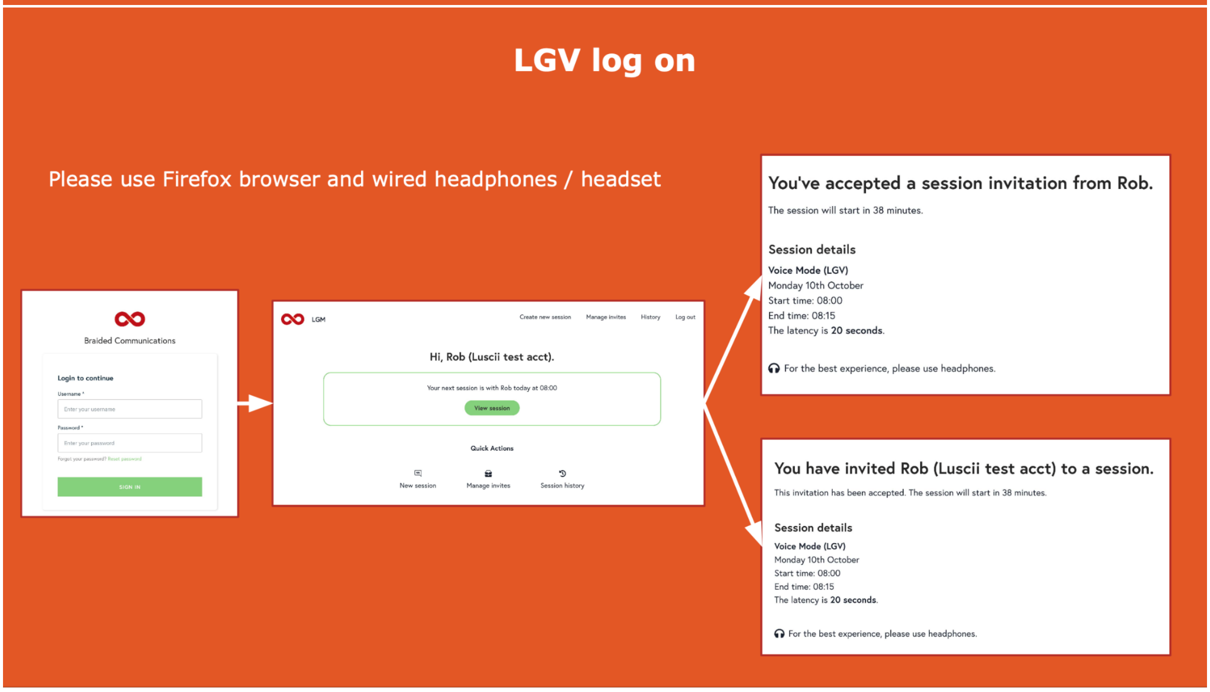
Rob Brougham & Drew Smithsimmons

team@braided.space
https://braided.space

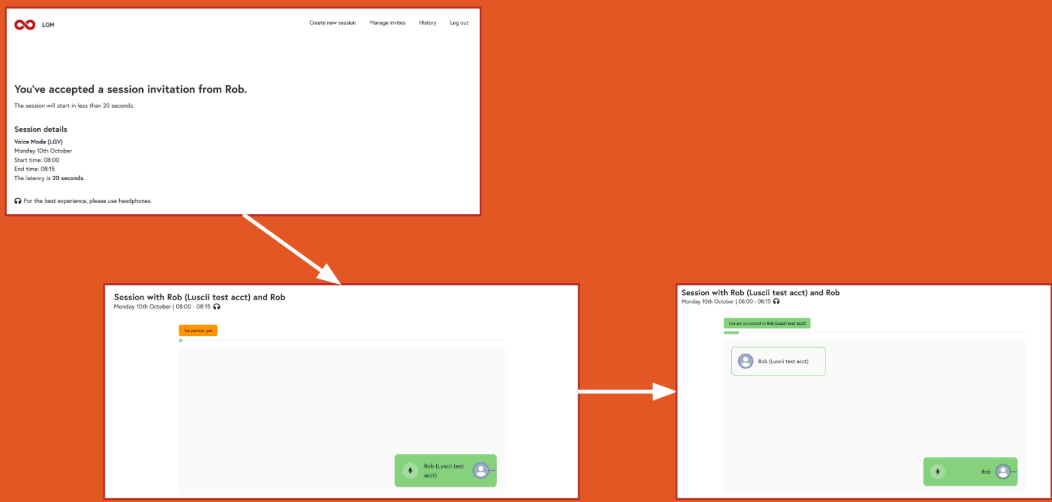
Agenda

1. A brief introduction to latency and the Edge of Voice experiment
2. How LGV works
3. Discussion and Q&A
4. Latency Governed Voice (LGV) trial sessions
5. Next steps


Typical latency profile for a conjunction class Mars mission
Vertical lines show Mars arrival and departure
One way latency in minutes
0
5
10
15
20
25
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 400 420 440 460 480 500 520 540 560 580 600 620 640 660 680 700 720 740 760 780 800 820 840 860 880 900
Time since Earth departure in days


LGV log on
Please use Firefox browser and wired headphones / headset
Braided Communications
Login to continue
SIGN IN
Hi, Rob (Luscii test acct).
Your next session is with Rob today at 08:00
View session
Quick Actions
New session
Manage invites
Session history
You've accepted a session invitation from Rob.
The session will start in 38 minutes.
Session details
Voice Mode (LGV)
Monday 10th October
Start time: 08:00
End time: 08:15
The latency is 20 seconds.
For the best experience, please use headphones.
You have invited Rob (Luscii test acct) to a session.
This invitation has been accepted. The session will start in 38 minutes.
Session details
Voice Mode (LGV)
Monday 10th October
Start time: 08:00
End time: 08:15
The latency is 20 seconds.
For the best experience, please use headphones.

LGV in action



Thank you

Rob Brougham & Drew Smithsimmons

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https://braided.space

Appendix IX

Powerpoint slides for High-Latency Psychological Therapies training

Background

The European Space Agency has funded Braided to investigate the impact of signal latency (time delay) on human communication in spaceflight.

NASA's Artemis program will return astronauts to the Moon and on to Mars.

SpaceX intends to go to Mars earlier.

The distances involved mean communication will be time-delayed.

Long duration exploration missions make mental health problems increasingly likely.

Industry assumption that psych support can only be asynchronous or DTx.

Study

Six highly skilled internet-enabled psychotherapists, working in pairs.

To conduct two role-plays, switching roles between therapist and the person in therapy.

Using space braiding, a communication tool that enables high-latency synchrony.

To investigate the feasibility of delivering a familiar component of evidence-based therapy in a realistic case vignette (common mental health problem).

Space Braiding

SB is a software application.

That arranges the subtopics of a conversation into braids on a carousel.

Presenting one active braid to the user for a given amount of time.

Before rotating right-to-left, to the next panel - the next active braid.

At any moment in time, users are on opposite sides of the carousel.

There is no ‘send’ button - When the time for the active braid is ended (signalled by a timer bar), the carousel will rotate to the next braid.

Task

In pairs, you will complete two 60 min role-plays.

Switching over in the role therapist and person between those two role-plays.

In the role of therapist, you will deliver the component of evidence-based therapy you have chosen in the context of the case vignette identified.

In the role of person, you will engage with the therapist from the point of view of the case vignette identified.

After each role-play you will provide brief feedback via a google form.

We will have a comfort break between the role-plays.

Data privacy provisions

We will use your email addresses to invite you to the training session, provide you with a Space Braiding, and send you the link to the Google Form outcome measure.

As therapists, you know not to include any personal information in the content of the role play.

The content of the session will not be analysed by the principal investigator for the purposes of this study.

We will ask you to confirm by email if you consent to the storage of the role-plays to.

If you do not consent to that, for any reason, you **are** very welcome to participate in the experiment all the same.

SB practice

In a moment, we will provide you with your login username and passwords.

When you login, you will click 'join session' to arrive in the lobby.

You will see a countdown and identified subtopics for the session.

Notice that the participants will start typing into different braids to one another.

Prepare for that.

There will be a smaller time delay implemented to allow for a short practice session.