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Investigating the Usability and Quality of Experience of Mobile Video-Conferencing Apps Among Bandwidth-Constrained Users in South Africa

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Abstract

During the COVID-19 pandemic and mandated global lockdowns, people and businesses started the extensive use of video-conferencing applications for staying connected. This surge in demand and the usability of video-conferencing services has been severely overlooked in developing countries like South Africa, where one-third of adults rely on mobile devices to access the internet, and the per-gigabyte data cost is among the highest in Africa. Considering these numbers, we conduct a two-pronged study where 1) we measure data consumption of different Android apps through data measurement experiments and 2) we conduct interviews and usability assessments with bandwidth-constrained users to better understand the usability and Quality of Experience (QoE) of mobile video-conferencing apps. Usability is the degree to which specified users can use a product to achieve specified goals. In contrast, QoE measures the subjective perception of the quality of an application and the level of delight or annoyance with a service. The key benefit of this study will be to inform organisations that seek to be inclusive about these tools' relative usability by letting them know about the factors influencing users' QoE.

1 Introduction

As countries restricted activities due to the COVID-19 pandemic, we have seen a surge in demand for video-conferencing apps as they became indispensable for professional and social purposes. Following global trends, this surge is also evident in the South African market [4]. However, in the South African landscape, where the majority of people connect to the internet using mobile devices [2], guaranteeing reliable end-to-end connections over wireless networks, such as Wi-Fi and cellular networks, is difficult [27, 31]. Interference, congestion [27] and sub-optimal interconnection between ISPs [14] can be attributed as the reasons for this difficulty.

However necessary, the performance and usability of video-conferencing applications is not well understood - especially over poor networks with bandwidth-constrained users. In this study, we unpack how users with bandwidth caps and poor internet connections utilise video-conferencing apps and their perceived QoE of these tools on mobile devices. We also explore the data consumption of the different applications. Due to South Africa's high mobile penetration rate and large Android market share, the measurement experiments only focus on the data usage between Android mobile applications over cellular networks [2]. To explore these research objectives, we formulated the following research questions:

- How do users with bandwidth constraints, and poor internet connections utilise video-conferencing apps, and what are their pain points?
- How do users with bandwidth constraints, and poor internet connections perceive the QoE of these tools?
- How does usability differ between the different applications for users with bandwidth constraints and poor internet connections?
- How does bandwidth usage differ between the Android video-conferencing mobile applications?

For the purpose of our research, we define a bandwidth-constrained user as a consumer limited by their infrastructure and/or finances to partake in the advantages of the internet. When referring to the term bandwidth, we do not refer to the technical definition, but the popular definition of bandwidht and as such the bandwidth of the end user.

2 Background

2.1 Bandwidth-constrained users in South Africa

Despite an increase in the adoption of internet-capable mobile devices [1], internet usage in South Africa is limited due to unequal coverage [2] and the cost of data [11]. Donner [12] found that the 'pay-as-you go' way of accessing the internet makes people constantly aware of the incremental cost of using their devices. Chetty *et al.*'s [9] research highlights that users with constraints tend to avoid high-bandwidth sites at the beginning of the month to stretch their caps to the end of the month when the meter starts running again. M-Lab reports that the average national broadband speed in South Africa in 2020 was 14.04 Mbps - ranking 97th globally[1]. Wyche [30] found that in resource-constrained settings, slow internet speeds affect users and highlight that their interactions are more planned, purposeful, and deliberate.

2.2 Network measurements in Africa and bandwidth usage experiments

Phokeer *et al.* [23] found that users in townships use cellular data networks relatively more than Wi-Fi networks. Chetty *et al.'s* [10] research established that mobile broadband consistently outperformed fixed broadband in terms of bandwidth and that a lack of interconnection among ISPs played a significant role in the performance experienced by users [10].

Yu *et al.* [32] conducted a measurement study of mobile video calls over Wi-Fi and cellular networks. They found that mobile video call quality is highly vulnerable to packet loss and packet delays [32]. With strong Wi-Fi/cellular connections, modern smartphones are capable of encoding, transmitting and decoding high-quality video in real-time [32]. Bieringa *et al.* [7] evaluated the performance of Zoom, Microsoft Teams and Jitsi on computer-based video-conferencing systems by using experiments to understand the resource requirements of these tools. Significant differences in the resource usage of the different systems were found [7]. Results indicated that, on average, Zoom had the highest resource usage and performance variability compared to Teams and Jitsi.

[1] https://www.cable.co.uk/broadband/speed/worldwide-speed-league/

2.3 QoE and Usability of video-conferencing apps

ISO 9241-11:2018 defines usability as "the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use" [13]. In contrast, QoE measures the subjective perception of the quality of an application and the degree of delight or annoyance with a service [17, 20]. It has been noted that usability and QoE each have their own unique set of evaluation methods.

The objective technology-centric approach of using the technical network performance metrics (Quality of Service (QoS)) has been the standard for demonstrating the usefulness of video-conferencing applications by relating QoE to system factors [26, 29]. Examples of these metrics/system factors include the bitrate, delay, network loss rate, traffic jitter, link delay, conversational condition, and loss concealment mechanisms [5, 25]. While the data-driven approach to understanding the usefulness of virtual conferencing applications (VCAs) through QoS metrics was well-accepted [26, 34], more recent research highlights the limitations of this approach. Systems excelling in QoS can fail user adoption and have a poor QoE due to the gap in users' experiences, and system evaluations [34]. Subjective QoE assessment thus requires users to self-report their perceived satisfaction [34], and this is often expressed in terms of Mean Opinion Scores (MOS).

Previous literature defines the field of Human-Computer Interaction (HCI) as a field "concerned with the design, evaluation, and implementation of interactive computing systems for human use and the study of major phenomena surrounding them" [21]. There are multiple methods to evaluate interactive computing systems within HCI. These methods include usability testing through task evaluation [6] and the System Usability Scale (SUS) [19]. Usability testing involves observing users while they use the product to understand its usability while SUS makes use of ten statements, listed below, to measure perceived usability by having participants indicate on a 5-point scale if they strongly disagree (1) or strongly agree (5) with the statement [18].

1. I think that I would like to use this application frequently.
2. I found the application unnecessarily complex.
3. I thought the application was easy to use.
4. I think that I would need the support of a technical person to be able to use this application.
5. I found the various functions in this application were well integrated.
6. I thought there was too much inconsistency in this application.
7. I would imagine that most people would learn to use this application very quickly.
8. I found the application very awkward to use.
9. I felt very confident using the application.
10. I needed to learn a lot of things before I could get going with this application.

3 Methodology

Our study utilised a two-pronged mixed methodological approach: 1) a set of experiments to compare data consumption of WhatsApp, Google Meet, Microsoft Teams and Zoom and 2) interviews with bandwidth-constrained users to better understand the usability and usage of these apps. The purpose of using mixed methods is to enable us to provide a comprehensive framework on both qualitative and quantitative data for each of the mobile video conferencing applications. Quantitative data obtained through interviews, usability studies and bandwidth measurement experiments provide descriptive statistics around data usage and usability of these applications. Whereas, the qualitative data obtained through interviews and usability testing allow us to gain deeper insights into our research questions.

To determine which apps to include in our research, we noted that, according to SensorTower, when South Africa went into lockdown in March 2020, Zoom, Teams and Google Meet were the most downloaded video-conferencing apps in the business category [2]. Whatsapp was the most downloaded communication app [3] in the South African Play Store. Assessing the validity of SensorTower's data, we note other studies utilise their data and insights when citing app engagement and performance [28].

3.1 Measurement experiments

We conducted multiple data usage measurements using PCAPdroid, an open-source Android application that lets users capture phone traffic without needing to root their devices [4]. Table 1 gives an overview of the different call configurations results.

Table 1: Call configurations tested during the measurement experiments

Call Configuration
One-on-one audio-video call over mobile data
One-on-one audio call over mobile data
One-on-one audio-video call over mobile data where one assistant switches off incoming video
One-on-one audio-video call over mobile data with data saving mode on
Group call over mobile data
One-on-one audio-video call over Wi-Fi

Each research assistant connected to the designated video-conferencing platform using mobile data and their personal Android phones for each experiment. Assistant A connected using a Samsung J5 with an MTN 4G connection (avg. upload/download speed 14.34Mbps/16.88Mbps) for mobile data calls and Faircape fibre connection (avg. upload-/download speed 14.96Mbps/17.38Mbps) for the Wi-Fi calls. Assistant B connected using a OnePlus 6T device with a Cell-C 4G connection (avg. upload/download speed 1.02Mbps/6.16Mbps) for mobile data calls and MWeb fibre for Wi-Fi calls (avg. upload/-download speed 4.27Mbps/15.50Mbps). We recruited additional research assistants to help with group calls. For group calls, we kept the group size consistent at 6 participants for each of the calls as per previous research [8].

We performed these measurements in a real-time environment to observe and validate the performance within real-life conditions. Before commencement of the sessions, the research assistants downloaded PCAPdroid and the video-conferencing apps onto their Android phones. Before each experiment, each assistant first measured and noted their internet speeds. They then selected the target application in the PCAPdroid application and started the packet capturing process. This was followed by a video call for a particular configuration between the participants. After 15 minutes, we ended the call and terminated the PCAPdroid's capture.

Due to internet speed variations, we measured internet speed before each call. We also repeated the experiments to check the variability of the results and increase our estimates' accuracy. Each one-on-one call was repeated three times per application, at the same time over three days. We repeated group calls twice in one afternoon, where each experiment call lasted

[2]https://sensortower.com/android/rankings/top/phone/south-africa/business
[3]https://sensortower.com/android/rankings/top/phone/south-africa/communication
[4]https://github.com/emanuele-f/PCAPdroid

15 minutes. Call duration was set based on previous QoS measurement studies, which used a call duration of 15 minutes [33, 15].

While QoS and QoE measurement studies frequently look at several different indicators, in this study, we focus only on total data consumption, including upload and download, since this has a financial impact on our pay-per-kb users and their ability to participate in calls at all, whereas other indicators speak to what is already well-known about network vs video quality.

3.2 Interviews

We recruited ten participants with bandwidth caps and/or a poor internet connection. We did convenience sampling by reaching out to organisations that utilise video conferencing and asking them to refer participants for the study. We removed participants' identities and assigned an abbreviation for each participant to ensure anonymity. The local university research ethics committee reviewed the protocol. We gave each participant 1GB of mobile data from their service provider to compensate them for the data used during the video-call interviews. Table 2 gives an overview of the participant demographics.

Table 2: Participant demographics. The values in column 5 and 6 indicate the self-assessed likert-scale familiarity with the application where 1 = not familiar and 5 = very familiar.

Participant	**Age**	**Gender**	**Native Language**	**APP1**	**APP2**
TS	22	M	Zulu	Google Meet (4)	Zoom (3)
PR	21	M	Zulu	Zoom (4)	Google Meet (5)
LC	34	F	Shona	WhatsApp (5)	Google Meet (1)
ST	39	F	Afrikaans	MS Teams (3)	Zoom (5)
BP	35	M	Zulu	WhatsApp (5)	MS Teams (1)
JJ	31	M	Kirund	WhatsApp (5)	Google Meet (1)
KS	20	F	Sepedi	MS Teams (3)	WhatsApp (5)
BO	42	M	Ga	WhatsApp (3)	Zoom (1)
MC	37	F	Chichewa	Google Meet (1)	MS Teams (1)
TM	37	F	Xhosa	Zoom (1)	Zoom (1)

To gain a deeper understanding of usability and QoE, we conducted remote semi-structured interviews and usability evaluations with these participants. Each participant was assigned two apps to test; the researchers selected which apps each user would test to ensure each app got evaluated five times. As we conducted the study remotely using the video-conferencing apps investigated in this paper, the interview was done in a single session of two video calls. Each participant had to join the interview remotely by downloading the applications specified by the researcher.

Once downloaded, users used their mobile devices and mobile data to connect to a video call using application 1(APP1). On APP1, we asked a few introductory interview questions. This was followed by task evaluation, QoE assessment and SUS assessment of APP1. Users then used their mobile devices and mobile data to connect to application 2(APP2). On APP2, we again performed task evaluation, QoE assessment and SUS assessment (sec 2.3). The interview ended with closing questions.

We transcribed the interview recordings and then imported the transcriptions into NVivo, a Qualitative Data Analysis (QDA) computer software package [5]. Using Nvivo, we analysed the data for codes and themes using the thematic data analysis method. Thematic data analysis is a method for identifying, analysing, and interpreting patterns/themes within qualitative data [3]. The data analysis was repeated until saturation was reached and no further coding could be applied.

3.3 Limitations of the study

Although the participants involved in the interviews were all bandwidth-constrained, this study makes use of a small sample and does not represent a representative sample for understanding usability and QoE. We do not provide data for statistical significance but rather present information to get varying perspectives about usability and QoE perceived by users with bandwidth constraints. Limitations of the measurement study include limited control over upload and download speed. As these experiments were conducted in real-time over mobile networks, measurement data might vary. Additionally, we found variance in some of our measurements data.

4 Findings: Measurements

4.1 Impact of internet speed

To determine whether there is a correlation between internet speed and data usage, we calculated the correlation coefficient between internet upload speed and data sent ($r(116) = 0.13, p = 0.15$) and between internet download speed and data received ($r(116) = 0.15, p = 0.10$). Although both these correlation coefficients are positive, they indicate a weak positive correlation; thus, in both instances, while both variables tend to go up in response to one another, the relationship is not very strong.

We observed a strong positive correlation between the megabytes sent by one assistant and the megabytes received by another assistant during one-on-one video calls. The coefficients were as high as 0.965 ($r(49) = 0.93, p = 0.00$) for $assistant\ A \rightarrow assistant\ B$ and 0.993 ($r(49) = 0.99, p = 0.00$) for $assistant\ B \rightarrow assistant\ A$. A marginally higher value for $assistant\ B \rightarrow assistant\ A$ can be attributed to A's superior connection speed.

4.2 Data consumption findings

For the audio-video calls over mobile data, Teams and Zoom used the most data during the 15-minute calls (Table 3). We note that the total data consumption when switching incoming video off is lesser than audio-video calls. In this configuration, we saw a decrease in the data consumption for both assistants even if only *assistant B* switched their incoming video off. On average, the total data usage was 63.03% less than an audio-video call over mobile data with incoming video on and 92,62% less on an audio-only call.

Configuration with data saving enabled was only done on WhatsApp as it is the only application in our study that enables it. The average data consumption for the three iterations was 39.94MB for the 15 min call duration. For comparison, the audio-video calls over mobile data consumed on average were 85.86MB (114.97% higher than data saving mode), whereas

[5] https://www.qsrinternational.com/nvivo-qualitative-data-analysis-software/home

Table 3: Average total MB used per configuration per platform. Missing values against an app indicates that that particular configuration is not available in the app.

Call Configuration	**Zoom**	**Teams**	**Meet**	**WhatsApp**
One-on-one audio-video call over mobile data	118.57	123.94	98.72	85.86
One-on-one audio call over mobile data	14.94	9.15	9.52	3.7
One-on-one audio-video call over mobile data where one assistant switches off incoming video	-	45.82	-	-
One-on-one audio-video call over mobile data with data saving mode on	-	-	-	39.94
Group call over mobile data	100.63	107.55	122.01	44.43
One-on-one audio-video call over Wi-Fi	244.14	109.3	107.39	158.87

the audio-only calls over mobile data used on average 3.70MB (90.74% lower than data saving mode).

When comparing audio-video calls over Wi-Fi, Zoom had the highest data consumption - consuming a total of 244.14MB. WhatsApp followed with average total consumption of 158.87MB. Google Meet used the least amount of data on average, consuming 107.39MB, which is 56.01% less data than Zoom. We also found that the data consumption for audio-video calls over mobile data was lower compared to audio-video calls over Wi-Fi. The total data usage is higher over Wi-Fi for Meet (8.79%), Zoom (105.9%) and WhatsApp (85.03%), but not for Teams (-11.81%), indicating that all the apps except Teams behave differently with varying network type. The data consumption for audio-only calls, on the other hand, was found to be significantly lower as compared to audio-video calls. WhatsApp used, on average, 95.68% less data. Microsoft Teams used 92.61% less, Google Meet used 90.35% less, and Zoom used 87.40% less.

For group calls over mobile data, we found that WhatsApp used the least amount of data, consuming on average 44.43MB over 15 minutes. Zoom consumed on average 100.63MB. Zoom used the second least amount of data , followed by WhatsApp. On both Teams' calls, one of the assistants had connection issues and got disconnected from the call; despite not having 6 assistants for the entire call duration, Teams used on average 107.55MB. On Google Meet, one assistant's mobile phone restarted during the call and had to reconnect. Nonetheless, Google Meet used the most data, on average consuming 122.01MB over the 15 minutes call.

5 Findings: Interviews

5.1 Participating in video-conferencing

We saw the participants' usage increased due to Covid-19. Most participants indicated that they used video-conferencing apps weekly in comparison to daily during the pandemic. Despite this, all participants indicated that data consumption of these apps is a concern. All participants indicated that they were reluctant to participate in video calls due to the data consumption of these tools. We also found that participants cannot freely participate in conference or social calls due to bandwidth constraints and are limited in when and how they use the applications.

Six (6) of the participants indicated that they tend to switch their video off to improve the quality of calls. Although WhatsApp has a data-saving mode, none of the participants who assessed WhatsApp listed it as an option to reduce data consumption, similar to Teams' functionality to switch incoming video off.

5.2 Lack of visibility and understanding of app data consumption

We also asked bandwidth-constrained users to tell us how much data a 20-minute one-on-one audio-video call would use. The answer varied between 100MB to 250MB. One participant indicated that she uses between 500MB to 1GB for an hour call and calculates the consumption. Three (3) out of the 10 participants answered 'they do not know' or 'a lot'.

Additionally, we asked participants how they monitor their data usage. We found that none of the participants used bandwidth monitoring applications. Participants LC, PR and MC indicated that they check their data balance before and after the call, whereas participant TC said she would predict how much data she would need to make a call. We found that participants had little understanding of how much data different applications used and there was limited visibility over the bandwidth the different apps use. We found that only WhatsApp showed data usage after a call has been completed.

5.3 WhatsApp is the preferred app of choice

We found that participants in white-collar environments (office/university) mostly used Meet, Zoom and Teams as they were required to use these apps. Also, these participants preferred different apps for different purposes. This could be due to them adopting a broader selection of apps for video-conferencing purposes. In comparison, participants who did not function in these environments mostly used and preferred WhatsApp as this was the app used the most by them.

It is possible that this could be connected to education level and/or occupation; however, we did not specifically ask participants what their highest level of education or job is. When users made a self-motivated decision regarding which application to use, WhatsApp was the preferred tool of choice. Participants preferred WhatsApp because it was convenient and cost-effective. WhatsApp has specific features to support lower data costs, but lacks support for screen sharing, and has limits on group call size - which increased from four participants to eight in April 2020. Understanding this in more depth is an area for future exploration.

5.4 Freedom of platform choice

We found that users do not really have a choice regarding which applications they can use. We discovered that their institutions mandate the adoption and use of specific video-conferencing apps. Five (5) out of the 10 participants indicated that they can only choose which platform to use to video call family and friends. We also discovered that when they do have a choice their decision is heavily impacted by the convenience of the platform and data constraints of the other participants in the call. Convenience related to 1) how many people have the application installed, 2) do they need to download the application before they can join a call, and 3) do they need an email address to join a meeting. Participant JJ noted that WhatsApp was more convenient because most people have it installed, whereas participant BO preferred Zoom as the people he conversed with prefer to use Zoom. Also, bandwidth constraints of the connecting users are limitations to participation. We found that if the other party to video call with are bandwidth-constrained, users tend to gravitate towards the more cost-effective platform for all participants joining the call.

5.5 Quality of Experience (QoE)

To measure QoE, participants rated the quality of each call using a MOS of 1 to 5, where 1 is bad and 5 is excellent. Table 4 gives an overview of the average QoE rating per platform. Participant BO could not get the audio for Zoom to connect whereas participant MC could not get Teams to work. Due to these technical issues, we asked them to rejoin the interview using APP 1. We then asked them to give a MOS rating for APP 2. Based on these MOS ratings, Google Meet had the best QoE, followed by WhatsApp, Zoom and Teams. Expanding on the ratings we found that key factors influencing MOS rating were audio lags and inconsistent video streams.

5.6 Application Usability Assessments

Table 4 gives an overview of the different evaluations. For the task evaluation, we present the average rating across the tasks of switching video on and off, switching their microphone on and off and sending in call messages. We only included these three tasks, as they were constant across all four platforms.

Table 4: QoE, SUS and task evaluation ratings per application.

Measurement	**WhatsApp**	**Meet**	**Teams**	**Zoom**
QoE (std.dev)	4 (1.22)	4.2 (0.44)	2 (1.41)	2.8 (1.09)
SUS (std.dev)	91 (9.46)	82 (12.17)	70 (33.48)	64.75 (26.89)
Task evaluation (std.dev)	4.53 (0.46)	4.53 (0.64)	3.75 (1.39)	4.17 (0.52)

5.6.1 System Usability Scale (SUS)

To determine the usability for each app, we asked participants to complete the SUS questionnaire. Table 4 gives an over of the average SUS score rating (out of 100) and the standard deviation. To determine the reliability of the SUS answers, we calculated Cronbach's alpha. Reliability is the extent to which an instrument will give the same results if the measurement is to be retaken under the same conditions [22]. We calculated Cronbach's alpha as $\alpha = 0.84$. Research shows that for the questionnaire to be reliable, the Cronbach's alpha values should be at least 0.70 [16]. SUS scores will be discussed in conjunction with the task evaluation findings.

5.6.2 Task Evaluation

During the task evaluation we observed that most participants had no issues with switching video on/off. Only participant TM had difficulty doing the task which could be related to her unfamiliarity with both the applications as she only uses WhatsApp. Furthermore, participants had no trouble switching their microphones on and off. In the sub-sections below we expand on the usability of each of the apps as well as on the usability issues observed.

Microsoft Teams According to our SUS evaluation Teams had an average SUS score of 70 (Table 4) which indicates C usability grade rating. The calculated standard deviation of 33.48 indicated that usability varied among the participants.The usability rating is also validated by the qualitative feedback we got from users. From the task evaluation, we found that 2 of the 4 participants found sending in-call messages and screen sharing difficult. Participants indicated that the most significant usability issues around sending in-call messages related to the positioning of the feature. Both participant ST and BP expected the functionality to sit at the bottom of the screen within the expanded context menu. For Microsoft Teams, we also explored if users knew what 'switch incoming video off' meant. We posed this question to all participants to determine if the feature labelling within the app was self-explanatory. Only 1 out of the 10 participants knew what 'switch incoming video' meant. Both participants BO and TS thought it meant rejecting an incoming call. We also found that none of the participants who evaluated Microsoft Teams knew that functionality is available on the Teams app. When we asked participants evaluating Teams to switch their incoming video off, they rated the difficulty 2 out of 5; indicating it was hard to find.

Zoom Although Zoom was the second most installed app among the participants, Zoom had the lowest average SUS score (table 4) among the apps. A score between 62.7 - 64.9 indicates a C- usability grade. The calculated standard deviation also indicated that usability varied among participants. During task evaluation we found that meeting pins and passwords adds cognitive load for users and it makes the application seem more difficult to use. Participant TS was noted saying that adding meeting pins and passwords makes it more intimidating to use, whereas participant BO stated it makes the application seem more challenging to use. We also found that participants got frustrated at the beginning of the call when trying to connect the audio and the video. For participant BO, this was especially challenging as he ended up aborting Zoom and continuing the interview on WhatsApp. Another frustration we observed related to having to download the app before one can participate in a call. User expectation was that once they click on the call link they will be able to join a video call without constraints.

Google Meet Based on our SUS evaluation WhatsApp had an average SUS score of 82 (table 4) which indicates A usability grade rating. The calculated standard deviation of 12.17; the second lowest variability among the app SUS scores. Despite the high usability score, we found during the task evaluations, usability issues around screen-sharing. Feedback from users indicated that there was no visual indicator to highlight that the screen was sharing. Despite this, our other qualitative data obtained through the interviews supports the higher SUS score as we noted positive feedback from participants.

WhatsApp During our interviews, we found that all of the participants had positive sentiments towards the usability of WhatsApp and it was often brought up by participants, even if they were not evaluating the applications. According to our SUS evaluation WhatsApp had an average SUS score of 91 (table 4) which indicates A+ usability grade rating. The calculated standard deviation of 9.46; the lowest variability among the app SUS scores. Participant LC and JJ noted that WhatsApp is easy to use for new users. Participant LC stated that although the experience between Google Meet and WhatsApp was the same, her familiarity with WhatsApp influenced how she felt about using the application.

6 Discussion

6.1 Comparing assessment methods

For this study, we use a human-centric approach by asking bandwidth-constrained users to self-report their QoE by giving a MOS rating, and discussed the factors impacting their rating. We found that many QoE and QoS aspects correspond and that technical performance is a user property residing in user perception. This aligns with findings published by Shin *et al.* [26]. Hoßfeld *et al.*'s [17] stated that having users give a MOS rating as an experience rating is a practical way to convey QoE. We, however, found that if we only used MOS, we would not have received additional insights into the factors influencing QoE and user experience. Taking a human-centric approach to QoE measurements was a worthwhile extension on MOS and allowed the effective unpacking of human factors influencing the perceived QoE.

Also, we found SUS to have high levels of reliability when calculating Cronbach's alpha. We saw that through SUS both Zoom and Teams had lower usability ratings than WhatsApp and Meet. This aligned with the qualitative data and task evaluation data. The findings from our SUS evaluation of Microsoft Teams align closely with with Pal *et al.*'s [22] findings. In our research, Zoom's usability score, however, differs from findings published by Sauro and Lewis [24]. Their results indicated better usability. Future research should be done by expanding the study to include more participants to make the results more generalisable. Future research can also be done around how SUS is perceived by different user groups, i.e. bandwidth-constrained users vs users who have no internet constraints. We also note that only utilising SUS scores would not have provided us with insights into usability issues per application and if usability has been met or not. Utilising task evaluation in combination with SUS enabled us to understand the usability constraints of each of the apps and validate our SUS scores with qualitative data.

Table 5 gives an overview of the findings per measurement tool. For the data usage we only showcase the average consumption for audio-video calls over mobile data. Whereas for the task evaluation, we present the average rating across the tasks of switching video on and off, switching their microphone on and off and sending in call messages. We only included these three tasks, as they were constant across all four platforms. Comparing the methods, we saw that the different ratings closely aligned. We also found that both MOS and SUS provides a good indication of QoE and usability, respectively.

Table 5: Comparison table of the findings per measurement metric and platform.

Measurement	**WhatsApp**	**Meet**	**Teams**	**Zoom**
Data usage (15 min call)	85. 86 MB	98.72 MB	123.94MB	118.57MB
QoE (std.dev)	4 (1.22)	4.2 (0.44)	2 (1.41)	2.8 (1.09)
SUS (std.dev)	91 (9.46)	82 (12.17)	70 (33.48)	64.75 (26.89)
Task evaluation (std.dev)(out of 5)	4.53 (0.46)	4.53 (0.64)	3.75 (1.39)	4.17 (0.52)

6.2 Implications for design

During our research, we found that bandwidth caps and poor internet connections are not the only hurdles these users need to overcome.

One of the first hurdles is often presented before participating in a call. Compelling users to download the app before participating in a video call presents a barrier to participation and adds to the cost of participation. This was explicitly the case with Zoom and WhatsApp, where users cannot join a video call on the mobile website and need to download the app to participate. Phokeer *et al.* [23] found that in South African township communities, a considerable amount of data gets used over cellular networks to do app installations and updates. They proposed finding a solution that enables people to update their mobile phones without consuming internet traffic. They also stated that if phone updates can be predicted, we could provide updates in a "localised" fashion to enable faster and less costly updates. Alternatively, we recommend that these platforms should be designed to allow mobile-only users to participate without being required to download the app, just like Google Meet and Teams.

The second hurdle users face relates to the decision around when to join a video call. We found that due to bandwidth constraints, users cannot freely join in a conference or social calls and, as such, are restricted in terms of when and how they use these apps. This is in line with research published by Donner[12] stating that constrained users tend to "dip and sip" instead of "surf the internet". We also found that these users try to conserve their airtime and data bundles to enable them to participate in calls when needed. Therefore, the users' metered mindset has a drag on effective and engaging use of the internet. We also observed that users tend to limit when and how they do video calls and that they tend to switch their video off or reduce call duration to conserve data. Chetty *et al.* [9] highlighted that bandwidth caps shape how, when, and for how long people browse. To ensure users can freely participate without a metered mindset, we need to continue to advocate for bandwidth-constrained users and call on practitioners, policymakers, and technologists to push downwards on data prices and make apps even more data-efficient.

The next hurdle users face relate to the usability of the different applications. Based on SUS, WhatsApp and Meet consistently had better SUS and task evaluation ratings while Teams and Zoom had more usability problems. The poor usability of Zoom was surprising as it was the second most downloaded app among the participants. Improving these apps by addressing the usability issues presented in section 5.6 ultimately has implications for design. One of the key usability issues across all the apps related to the lack of visibility of data consumption. We found that users had little visibility of the bandwidth consumption of the apps. This prevents users from understanding what is depleting their data and limits them in managing bandwidth consumption. In line with Donner's [12] recommendations, one way to enhance the usability of video-conferencing apps is to create greater visibility and control around data usage of these apps. Chetty *et al.* [9] also advocates for creating better visibility of app data consumption.

The next hurdle users face is the monetary cost of participation. According to Chetty *et al.* [9], bandwidth caps force people to put a monetary price on their internet use. Our measurements shed light on the data usage of the different call configurations and platforms and give an overview of how much a call would cost. It highlights that data saving features such as 'data saving mode' and a feature to 'switch incoming video off' reduced data consumption. Despite this, users had little knowledge or understanding of these features and that it could reduce the monetary cost of participation. Based on these findings, we recommend developing features to notify users when connecting using mobile data and asking them if they want to switch to data saving mobile or if they want to disable incoming video.

6.3 Implications for organisations and institutions

We found that users often do not have a choice when it comes to which applications get used. These findings are similar to findings published by Phokeer *et al.* [23] about resourced-constrained communities not having a choice of connection type to access the internet. Therefore it should be recognised that organisations and institutions might impose a higher burden on participants when mandating the use of a specific video-conferencing application. Thus, we urge them to holistically look at the data consumption, usability, QoE and functionality of the different apps before mandating their use. We also posit the following implications for organisations and institutions:

Companies and organisations should ensure that the users can connect by providing them with data or a Wi-Fi dongle. Additionally, it should be noted that call configurations impact data usage for participants. Our study reveals that data consumption differed between the configurations. If possible, audio-only calls should be utilised or users should be encouraged to only switch video on when talking.

We also recommend that users should be educated on how to reduce data consumption when using mandated apps. This would enable them to control their consumption and make informed choices.

Finally, we want to emphasise the importance of organisations and institutions shifting towards mobile-centric consumers and continuing to support initiatives to lower data costs. Advocating for bandwidth-constrained users and putting pressure on telecommunication companies to reduce data costs should be a continuous endeavour to ensure inclusion and equal participation.

7 Conclusions

At the onset of the Covid-19 pandemic lockdowns, everything from education to work to socialising shifted to "online-only". As a consequence, video-conferencing apps were rapidly adopted and used to ensure people stay connected. This study unpacked the usability and QoE of mobile video-conferencing apps among bandwidth-constrained users in South Africa. We also examined how data consumption differs between Zoom, Microsoft Teams, Google Meet and WhatsApp mobile apps over mobile networks. This study posits implications for design to improve usability. We give practical recommendations on how these applications should be developed to accommodate bandwidth-constrained and 'pay-as-you-go' users. Our data usage measurement experiments shed light on the cost of participation and that, despite mobile data usage optimisation, policymakers and network operators should continuously focus on driving the cost of data down. Lastly, our research highlights that if organisations are going to mandate using specific video-conferencing applications, they should be conscious of user constraints and limitations to ensure inclusion and equal participation.

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