A Prototype Mixer to Improve Cross-Modal Attention During Audio Mixing

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ABSTRACT

The Channel Strip mixer found on physical mixing desks is the primary Graphical User Interface design for most Digital Audio Workstations. While this metaphor provides transferable knowledge from hardware, there may be a risk that it does not always translate well into screen-based mixers. For example, the need to search through several windows of mix information may inhibit the engagement and 'flow' of the mixing process, and the subsequent screen management required to access the mixer across multiple windows can place high cognitive load on working memory and overload the limited capacity of the visual mechanism. This paper trials an eight-channel proto-type mixer which uses a novel approach to the mixer design to address these issues. The mixer uses an overview of the visual interface and employs multivariate data objects for channel parameters which can be filtered by the user. Our results suggest that this design, by reducing both the complexity of visual search and the amount of visual feedback on the screen at any one time, leads to improved results in terms of visual search, critical listening and mixing workflow.

CCS CONCEPTS

• Information systems→ Multimedia and multimodal retrieval;

• Human-centered computing → Information visualization.

KEYWORDS

Audio Mixing, Interaction Design, Critical Listening, Digital Audio Workstations.

ACM Reference format:

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1 INTRODUCTION

The Channel Strip (CS) mixer found on physical mixing desks is the primary Graphical User Interface (GUI) design for most Digital Audio Workstations (DAWs). While this metaphor is familiar and provides transferable knowledge from hardware, there may be a risk that it does not always translate well into virtual representations [1]. For example, while a dial on the physical desk suggests and supports the perceived affordance of turning, this action is not supported when using a mouse, potentially leading to errors and breaks in the user's engagement with the task [2]. Furthermore, when using dials to adjust pan position in CS mixers, the user must look at the position of the pan dials for every channel to get a sense of the lateral position of a source, which may impede the ability to globally visualise the panning of sound sources between the speakers [3,4]. This is further compounded when using DAWs, as not all the channels may be visible on one screen, necessitating visual search across multiple pages to ascertain the panning of individual channels.

There are also perceptual issues to consider. While physical mixing desks are often limited to 24 channels, DAWs offer potentially limitless tracks for an audio mix, giving rise to situations where there may be too many channels to fit onto one screen. The subsequent screen management required to access the mixer across multiple windows can place high cognitive load on short-term and working memory (WM) [5], overload the limited capacity of the visual mechanism [6] and lead to a reduction in critical listening skills [7]. Moreover, the need to search through several windows of mix information may inhibit the engagement with the mixing process and impede the user's ability to quickly respond to the programme material [3,4,8], leading to a situation where some users find it "impossible to navigate those interfaces [Logic, Pro Tools] while also trying to be artistic" [9, p.12].

Moreover, since the late 1990s, there has been a shift in the demographic of DAW users from traditional studio environments to home studio-based recording and production [10]. This change may require interface designers to broaden the definition of a DAW user beyond a functional professional, performing in a commercial environment. Indeed, some users of music production software may have never used a physical mixing desk [11]. For such users, an alternative metaphor, which can be used alongside the more segmented mixing desk metaphor, may help maintain the user's creative engagement with the mixing process and provide different contexts of use [12]. Being aware of the perceptual issues while undertaking screen-based mixing, as well as the profile of non-expert and novice users, and designing interfaces which acknowledge these factors, may allow developers to enable users to engage in more efficient workflow, and allow visual feedback to better support critical listening.

This paper trials an eight-channel proto-type mixer which uses a Stage metaphor (SM) mixer design. The mixer uses an overview of the GUI and employs multivariate data objects for channel parameters (volume, panning, reverb, treble and bass controls) which can be filtered by the user, per their requirements. By so doing, the design minimises screen navigation, eschews the 1-2-1 mapping of controls to mix parameters found in CS design, and reduces both the complexity of visual search and the amount of visual feedback on the screen at any one time. We undertake a range of mixing tasks using this mixer and compare it to a CS mixer design to investigate whether the novel design affects the results in terms of critical listening, visual search and workflow speed.

2 STUDY DESIGN

Interface Design

Three eight-channel mixers were designed using Max/MSP. These comprised a CS mixer, an SM mixer, and a hybrid design mixer (combining functionality from both the CS and stage mixers). All designs showed each channel's volume, pan, reverb, treble and bass controls (figures 1).

For the CS design, faders were used to adjust volume, while dials were used for the pan position, treble, bass and reverb amounts. For the SM and hybrid designs, each channel was represented as a circle (using Max/MSP's nodes object). Each channel's x and y position were used to adjust pan and volume respectively, while the relative size of each channel's circle was used to represent and control either the reverb, bass or treble (figure 2). Clicking and dragging up or down on the nodes increased or decreased the circle size and the corresponding parameter value respectively. The choice of size to represent and modify frequency and effect amounts was in response to a previous study by the authors [13], which showed this to be the most easily identifiable visual channel for showing mix parameter differences (compared to transparency, colour or saturation).

As node size was used for reverb, treble and bass, each parameter was viewed separately by pressing modifier keys. Pressing 'r' displayed the channel's reverb amounts, pressing 't' displayed treble, and pressing 'b' displayed the bass. When this was done, the pan position and volume of the channels remained constant, with only the circle size changing accordingly (figure 2). As soon as the modifier key was released, channels returned to the default view, in which all channel circles were the same size, regardless of parameter values. The decision to assign all three parameters to size was included in response to two concerns. Firstly, previous studies by the authors [13,14] had suggested that filtering the amount of information in the interface decreased visual search times (without any reduction in concurrent critical listening response). Secondly, it addressed concerns that when using an SM design, the legibility of the GUI may become compromised as multiple channel parameters are displayed simultaneously.

For all interfaces, the EQ used the MAX/MSP filtergraph parametric EQ. The treble control had a centre frequency of 5000 Hz, with a fixed bandwidth of 1.33 octaves and a boost and attenuation range of +18 dB and -18 dB respectively. The bass band had a centre frequency of 125 Hz, with a fixed bandwidth of 1.33 octaves and a boost and attenuation range of +18 dB and -18 dB respectively. The reverb used the Max/MSP 'reverb2' object, and the mixers controlled the wet/ dry level (wet refers to reverberant sound, dry refers to lack of reverb), with a range of 0 to 100%.

Finally, in the SM and hybrid designs, a list of names of the tracks could be clicked (e.g., bass, vocal etc.) to highlight the appropriate channel (figure 3). This was done to address the random distribution of channels, and potential problems of searching through the interface to find a target channel. We did not include this functionality in the CS design, where the channels are in a fixed numerical position, left to right, at all times and were labelled for ease of identification.

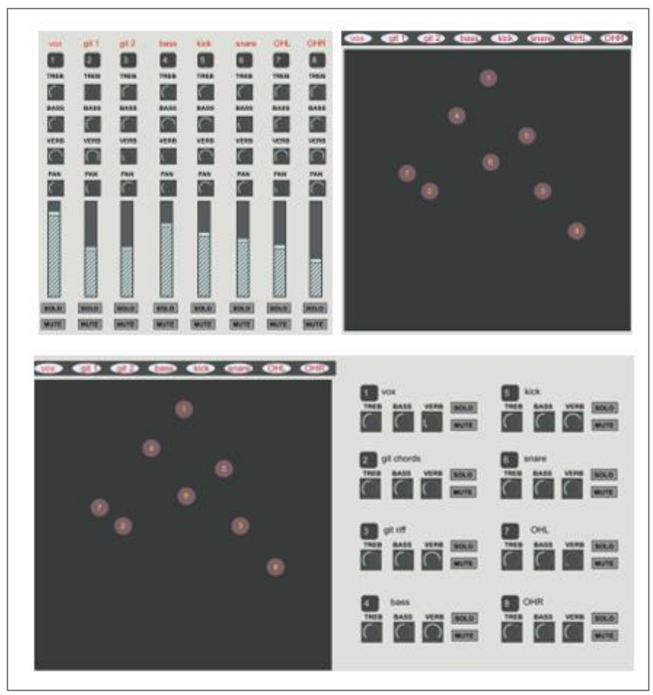

Figure 1. The three mixer designs used in the study. Top left, CS mixer. Top right, SM mixer. Bottom, hybrid mixer (combining the SM functionality with dials for treble, bass and reverb controls).

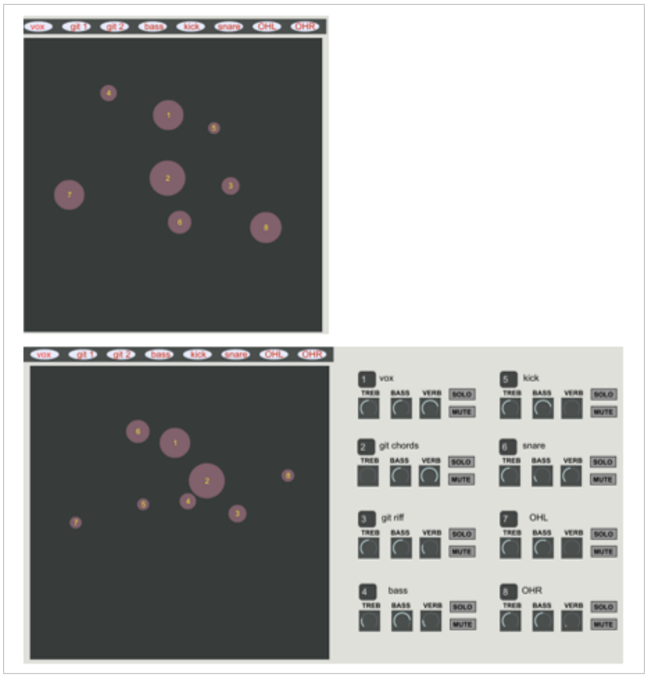

Figure 2. Size differences between channels for SM mixer (top) and hybrid (bottom). This allows users to see values of either treble, bass or reverb. Only one parameter can be viewed at one time. In the hybrid design, values are also displayed as dials.

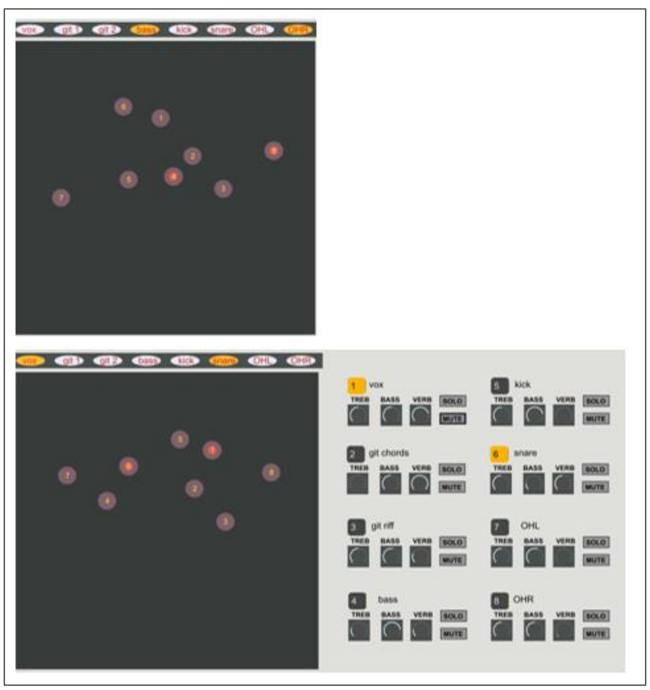

Figure 3. Selecting the instruments from the list at the top of the screen highlights the relevant channel(s). This functionality was not added to the CS design, as the channel order remains constant.

The decision to include a hybrid design was informed by three considerations. Firstly, we wished to investigate whether there might be disorientation effects in jumping from one view to another (as found in the SM design when using the modifier keys). As the hybrid mixer included dials as well as circles for the reverb, bass and treble values, it provided a secondary, constantly visible representation for these parameters. Secondly, we wished to assess whether layering of mix attributes (where only one parameter can be seen at one time) might slow down the mixing process [15]. Finally, we sought to address whether including a secondary source of information may influence WM or affect limits of visual bandwidth.

Participants

Twenty-four participants took part in this study. All the participants were drawn from the same population, namely first year students on a two-year music technology course at City and Islington College, London. The experiment used an Independent Measures design, requiring participants to use only one of the three experimental interfaces being tested. To compensate for potential variations between participants, we ensured they all had comparable experience of DAW mixing, and equivalent training in audio mixing. This was verified by comparing the experience of participants, none of whom had previous formal training in audio mixing prior to enrolling at the college and were all at the same stage of the course. The participants were randomly assigned to their particular mixer design, with eight participants using each interface.

3 PROCEDURE

Pre-Test Screening

Three eight-channel practice mixes were created using royalty-free audio recordings. Before the experiment began, each participant was individually played each mix of the tracks (without any mixer or visual feedback). During this time, three separate instruments (vocal, high-hat, and electric guitar) each had a Low Pass (LP) filter (-18 dB cut, 3000 Hz centre frequency, bandwidth of 2 octaves) applied for three seconds (one instrument per mix). As soon as they heard it, participants were asked to identify which instrument had the LP filter applied. Any participants who were not able to identify the instrument would have their results removed from the study. In the event, all participants answered these screening questions correctly, suggesting that without any visual stimuli, it is possible for the participants to clearly discern and identify this level of frequency attenuation within an audio mix.

Test Procedure

For the actual test, an eight-channel mix (duration 2 minutes 50 seconds) was created using royalty free samples (see table 1 for list of instruments), which was used in all interface designs. Each participant was shown the interface design that they would be using. This was either the CS, SM or hybrid design. The controls and functionality of the interface design were explained, and the participants were given time to practice using the mixer with a separate eight-channel mix. This was not time-bound, and participants were informed that they could spend as much time as they liked building their familiarity and confidence with the interfaces. Once they were happy they were told to begin the experiment.

Track	*Description*
Kick	Mono acoustic kick drum
Snare	Mono acoustic snare drum
Over-head L	Mono over-head drum kit recording- panned left
Over-head R	Mono over-head drum kit recording- panned right
Bass	Mono electric bass
Guitar	Mono electric guitar chords
Guitar 2	Mono arpeggiated guitar riff
Vocal	Mono male vocal

Table 1. The list of instruments used in the multi-track recording given to the participants. Eight tracks are typical of a small studio or Live Sound mix.

Pressing a 'ready' button on the screen revealed the first of six mixing tasks, written as text on the screen (table 2). The tasks included in the study were chosen as they deal with the fundamental elements common to good mixes [16]. These comprise balance: the volume level between musical elements, frequency range: the correct balance of frequencies in the mix, panorama: correct placement of sounds in the stereo field, and dimension: creating depth and ambience through use of reverb [17, p.10].

Once the participants had read the mixing task, and acknowledged that they understood what was required, they were told to press the 'start' button. Once pressed, the mixer appeared on the screen, the audio of the eight-channel mix started, and the participants began undertaking the required mixing task. During the mixing process, the LP filter was applied for three seconds to one of the three specified instruments (vocal, high-hat, or electric guitar 2) within a randomised period of 2-12 seconds of the participant interacting with the interface controls (e.g. moving a dial, clicking on a channel etc.). This was done to ensure that the visual and auditory tasks were completed simultaneously. Once the mixing task was complete, the participants were asked to press a 'finish' button. This saved their mix and completion time, and revealed a screen asking them to select which of the three specified instruments had the LP filter applied. This list included a 'couldn't tell' option to discourage the participants from guessing. As soon as they had entered their response, the mix reset and the instructions for the next mixing task was presented on the screen. This procedure was repeated for all six mixing tasks.

Mixing Tasks

The six mixing tasks presented to the participants ranged in the level of difficulty of visual search (table 2). Tasks 1 and 2 required users to visually search for one User Interface (UI) object to complete the mixing procedure (e.g. the position of the bass dial/ circle size). Tasks 3 and 4 required visual search for two UI objects, while tasks 5 and 6 required participants to search for three UI objects. Participants were not asked to mute or EQ the target channels (those which had the LP filter applied to them) in any of the tasks. This was done to ensure that these tracks were always audible and remained constant in frequency balance, thereby allowing users to hear any frequency attenuation. The order of the mixing tasks was randomised so that the difficulty was not progressive and improvements due to learning and practice were minimised.

Question	*Mixing task presented to participants*	*No. of UI objects*	*UI Object type*
1	Match the bass of channel 7 to channel 8	1	Bass
2	Mute all channels with volume below the bass.	1	Volume
3	Remove reverb on the channel panned furthest left and the channel panned furthest right.	2	Reverb / panning
4	Pan tracks with most bass to same position as channel 3	2	Panning / bass
5	Mute channels panned left of channel 4 which have more reverb, but less treble.	3	Panning/ reverb / treble
6	Mute any channels which have volume below the snare, more bass than the snare and more reverb than the snare.	3	Volume / bass / reverb

Table 2. Mixing tasks given during the experiment. The number of User Interface objects that need to be checked to complete the mixing tasks vary between 1 and 3, with two questions for each.

4 ANALYSIS

The time taken to correctly perform the mixing tasks, and the time taken to discern the LP filters were analysed for each participant. From this, the mean time and Standard Deviation (SD) were calculated per interface type. This was used to provide Confidence Intervals (CI), at 95%, to ascertain if correctly completing the mixing tasks or hearing the frequency attenuation was faster on any of the interface designs. The amount of correctly completed mixing tasks (adjusting the correct parameters on the correct channels) and correctly discerned LP filter were also recorded and analysed for each participant. This data was then subjected to a *z*-test for proportions, to ascertain if there were any significant differences between interface designs.

Speed to Complete Mixing Tasks

The analysis of task completion time (figure 4), shows that mixing tasks which required analysis of one UI object did not result in any significant time difference between the designs. At two parameters, however, the CS was significantly slower than the hybrid and SM design. At three parameters, the amount of correct answers from participants using the CS design was so small that it resulted in a margin of error too large to create a meaningful CI figure. For the hybrid and SM designs, the speed of completion remained constant between one and two UI objects, becoming significantly slower when three UI objects were involved. However, even with three UI objects, they still resulted in faster mean completion times than two UI objects in the CS mixer.

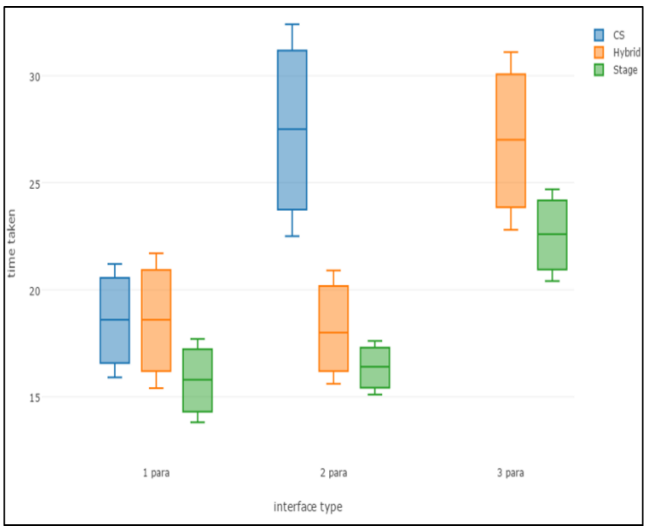

Figure 4. Confidence Intervals for time taken to correctly complete mixing tasks (in seconds) by interface type and UI paramter amount. When more than one UI object needed to be checked to complete the mixing task, the mean time was significantly worse for the CS compared to the other designs

Amount of Correctly Completed Tasks

The *z*-test for proportions analysis (table 3) shows that in terms of task completion, the difference between interface designs was not significant when one or two UI objects had to be searched for. However, when searching for and analysing three UI objects, a significantly greater number of participants correctly completed the tasks with the hybrid and SM mixers. Analysis of correctly identifying the channel with the LP filter shows a similar trend (table 4). When two or three UI objects had to be found and analysed, the percentage of participants who successfully identified the frequency attenuation increased significantly with the SM and hybrid designs, compared to the CS.

Finally, the *z*-test analysis for the percentage of users per interface type who completed the mixing task and the listening task (table 5), showed that results were significantly improved with the SM and hybrid mixers compared to the CS design in all the mixing tasks involving more than one UI object.

Parameters	*CS*	*Hybrid*	*Stage*	*Significant?*
1	87.5 (7)	100 (8)	100 (8)	N
2	87.5 (7)	87.5 (7)	87.5 (7)	N
3	50 (4)	75 (6)	87.5 (7)	Y

Table 3. Mixing tasks. Percentage of participants correctly completing the mixing task (per interface type and parameter amount) with the significance of difference between CS and hybrid/ SM designs.

Parameters	*CS*	*Hybrid*	*Stage*	*Significant?*
1	87.5 (7)	100 (8)	100 (8)	N
2	50 (4)	100 (8)	87.5 (7)	Y
3	25 (2)	87.5 (7)	87.5 (7)	Y

Table 4. LP filter. Percentage of participants who successfully identified the LP filter per interface type and parameter amount, with significance of difference between CS and hybrid/ SM designs.

Parameters	*CS*	*Hybrid*	*Stage*	*Significant?*
1	87.5 (7)	100 (8)	100 (8)	N
2	37.5 (3)	87.5 (7)	87.5 (7)	Y
3	12.5 (1)	75 (6)	87.5 (7)	Y

Table 5. Both tasks. Percentage of participants who successfully completed both tasks (correct mixing *and* hearing LP filter), per interface type and parameter amount, with significance of difference between CS and hybrid/ SM designs.

5 DISCUSSION

In all three GUI designs, the ability to correctly notice the LP filter reduced as the number of UI objects to be searched and analysed increased. This reduction was greatest when using the CS mixer (figure 5), with a 62.5% reduction in the ability to hear the LP filter when searching through three UI objects compared to one. In comparison, the SM and hybrid designs resulted in a less marked correlation between visual search complexity and aural acuity. In the hybrid design, there was a reduction of 25% in the number of participants who heard the LP filter when searching through three UI objects compared to one. For the SM design, this was further reduced to 12.5%. In fact, with the SM design, almost as many participants successfully heard the LP filter when searching through three UI objects, as participants using the CS design did when searching one.

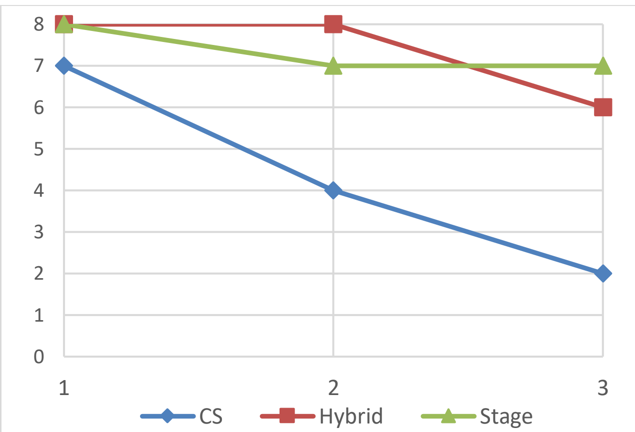

Figure 5. The reduction in number of participants (Y-axis) to correctly identify the LP filter per UI object amount (X-axis)

The fact that the impact of increased visual search was less marked in the SM and hybrid designs may have been due not only to the design of the GUI, but also to the modifier key functionality included in the novel interface designs. An observed strategy among participants using the novel designs was a toggling between views. For example, participants, were seen to rapidly check conditions of channels (such as the amount of bass and reverb) to ascertain which channels needed to be modified. This was especially marked in the tasks involving three UI objects. As comparisons of data sets can be made most efficiently via eye movements [18], the quick visual comparison may have helped minimise the load on visual WM and consequently reduced the search times [19]. Conversely, the intricacies of the CS mixer may have contributed to the slower and less accurate visual search. Indeed, it's design may have caused participants to engage in inefficient search, subsequently directing attention away from the audio itself [20].

Potential concerns over disorientation effects caused by modifier keys in the SM design seem not to have been a factor. In fact, the converse appears to be true, with the ability to rapidly change view appearing to be an advantage, rather than an impediment. This conclusion is further confirmed by the differences in the results between the stage and hybrid designs. The secondary, stable source of information provided by the dials in the hybrid design lead to a slight reduction in task speed and ability to discern the LP filter. This may have simply been due to users double checking the result with both sources of information (nodes and dials). However, the effects of Information Redundancy [21] present in the hybrid interface and the subsequent increase in UI objects may have resulted in a level of visual feedback surpassing that which can be efficiently processed in WM [22]. Nevertheless, the differences were minimal, and inclusion of dials may be useful on a more subjective level as a confidence-builder in an otherwise unfamiliar interface design.

6 CONCLUSION

In this study, we carried out mixing tasks addressing fundamental aspects of successful audio mixing workflow [16,17]. Our results show that as visual complexity increases, aural acuity diminishes for all the designs used in the study. However, the results of this experiment suggest that by presenting channels as multivariate data objects, users can more accurately make visual comparisons of mix parameters compared to 1-2-1 mapping of the CS layout, resulting in a faster more accurate visual search and improved critical listening. Furthermore, and somewhat unexpectedly, the use of modifier keys to show/hide mix parameters (such as effects and frequency) not only minimised screen clutter, but by supporting rapid toggling between parameters, allowed quick visual referencing between channels. We suggest this attribute of the functionality may have reduced WM load and allowed resources to be better shared between visual and aural modalities, resulting in faster and more accurate mixing, and better awareness of the LP filter being applied to the audio.

Providing a secondary, stable source of information in the hybrid design (dials as well as node size) did not seem to offer any improvements in speed or accuracy of the tasks, but neither did it significantly worsen them. Providing dials, faders or ordinal information (such as dB, Hz etc.) may help users gain confidence and make fine adjustments, though in future designs these may be better displayed in response to user requirements, rather than being constantly visible.

We feel that our study highlights the extent to which the visual feedback in screen-based mixing affects workflow, and we are not alone in taking such a view. Researchers have commented on the way that mixing engineers approach mixing visually as much as aurally [11, 20] while audio mixing guides regularly give guidance on how best to use visual metering and analysis tools to assist the mixing process, citing them as a useful way to deal with poor monitoring or room acoustics. Given this reliance on visual referencing in mixing, we believe that minimising the complexity of visual search and making the visual feedback perceptually more appropriate may benefit users. In line with this, the GUI presentation used in the novel designs, such as showing parameter amount by size or colour amounts, filtering the amount of visual data, or highlighting certain channels, may be transferable to the CS mixer, potentially allowing faster visual referencing of the mix and more efficient mixing workflow using standard DAW designs as well as novel interfaces.

REFERENCES

[1] Mihnkern, K. (1997). Visual interaction design: Beyond the interface metaphor. SIGCHI Bulletin, 29 (2), pp. 11-15.

[2] McGrenere, J. and Ho, W. (2000). Affordances: Clarifying and evolving a concept. In: Proceedings of the Graphics Interface, Quebec, May 15-17. Canadian Human-Computer Communications Society, pp. 179 – 186

[3] Gelineck, S., Overholt., D., Buchert, M. and Andersen, J. (2013) "Towards an Interface for Music Mixing based on Smart Tangibles and Multitouch." in Proceedings of the International Conference on New Interfaces for Musical Expression, May 27-30, Seoul, South Korea. pp. 180–185

[4] Mycroft, J., Stockman, T., and Reiss, J.D. (2015). 'Audio Mixing Displays: The Influence of Overviews on Information Search and Critical Listening'. In: Proceedings of Computer Music Multidisciplinary Research, June 2015, Plymouth, U.K

[5] Shneiderman, B. and Bederson, B. (2005). Maintaining Concentration to Achieve Task Completion. In: Proceedings DUX '05.

[6] Rensink, R. (2012). The Management of Human Attention in Visual Displays. In: Roda, C (ed.), Human Attention in Digital Environments. Cambridge University Press. pp.63-92.

[7] Mycroft, J., Reiss J.D., and Stockman, T. (2013) 'The Influence of Graphical User Interface Design on Critical Listening Skills'. In: Proceedings of the Sound and Music Computing, June 2013. Stockholm, Sweden.

[8] Szalva, W. (2009) Behind the Gear. Tape Op Magazine, No.73, pages 10-11.

[9] Crane, L (2010). This is your Brain Creating and Recording Music. In: Tape Op, No.74, p.12.

[10] Leyshon, A. (2009). The software slump? Digital music, the democratisation of technology, and the decline of the recording studio sector within the musical economy. Environment and Planning 41, pp.1309–1331.

[11] Battino, D. & Richards, K. (2005). The Art of Digital Music. San Francisco, Backbeat Books Crane, L (2010). This is your Brain Creating and Recording Music. In: Tape Op, No.74, p.12

[12] Gelineck, S., Overholt., D., Buchert, M. and Andersen, J. (2013b) Towards a more Flexible and Creative Music Mixing Interface. In: Proceedings of ACM SIGCHI Conference on Human Factors in Computing Systems, April 27 - May 02, Paris, France. ACM, pp.733-738#

[13] Mycroft, J., Stockman, T., and Reiss, J.D. (2016). 'Visual Information Search in Digital Audio Workstations'. In: Proceedings of Audio Engineering Society, June 2016. Paris, France.

[14] Mycroft, J., Stockman, T., and Reiss, J.D. (2016). 'Visually Representing and Interpreting Multivariate Data for Audio Mixing' In: Proceedings of Sound and Music Computing, August 2016, Hamburg, Germany.

[15] Liebman, N., Nagara, M., Spiewla, J., and Zolkosky, E (2010). Cuebert: A new mixing board concept for musical theatre. In: Proceedings of the International Conference on New Interfaces for Musical Expression, Sydney, Australia, June 15-18th. pp. 51-56.

[16] Moylan, W. (2007). Understanding and Crafting the Mix: The Art of Recording, 2nd Edition. Oxford, Focal Press.

[17] Owsinski, B. (2006). The Mixing Engineers Handbook. Boston, MA, Thomson Learning Inc.

[18] Plumlee, M. D. and Ware C (2006). Zooming versus multiple window interfaces: Cognitive costs of visual comparisons. Computer-Human Interactions.,13(2), pp.179– 209

[19] Baldano, M.Q.W., Woodruff, A. and Kuchinsky, A. (2000). Guidelines for using multiple views in information visualization. In: Proceedings of Audio Visual Interfaces, Palermo, Italy. New York, ACM Press. pp. 110–119.

[20] Dewey, C. and Wakefield, J. (2016). Audio Interfaces Should be Designed Based on Data Visualisation First Principles. In: Proceedings of the 2nd AES Workshop on Intelligent Music Production, London, UK.

[21] Sweller, J. (1988). Cognitive Load During Problem Solving: Effects on Learning. In: Cognitive Science 12, 257-285

[22] Baddeley, A. (2003) Working memory and language: An overview. Journal of Communication Disorders 36, pp.189–20