The Use of Virtual Tabletop for Revising Electron Counting in Inorganic Chemistry

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Abstract
Electron counting of metal complexes is an important skill for chemistry undergraduate students learning inorganic chemistry. As part of game-based learning, we have developed a card game termed "CountQuest" for students to revise electron counting after learning this concept from conventional lectures. In this proceeding, we describe the use of a free web-based virtual tabletop platform, playcards.io for implementing an online version of CountQuest due to COVID-19 restrictions in 2021. Pre- and post- game surveys indicated that students' confidence in electron counting improved to a large extent. Pre- and post-game quiz results at 5% significance level indicated that there is a significant difference between quiz scores. The students' perception of confidence in electron counting showed improvement after playing CountQuest in all three years that the game was played, independent of the mode of delivery of the game (physical or online).

Keywords: Game-Based Learning, Virtual Tabletop, Electron Counting

Introduction

Electron counting is a foundational concept for inorganic chemistry. Metal complexes are compounds that consist of a central metal center (M) surrounded by electron donating ligands (L). The electron count of octahedral metal complexes is typically 18 (thus "18-electron rule") due to the filling of 9 bonding molecular orbitals while the antibonding orbitals are vacant (Sidgwick, 1934). As part of the learning objectives for the module CM2111: Inorganic Chemistry 2, students are expected to perform electron counting of metal complexes by adding the valence electron count from the metal center and ligands respectively. Achieving proficiency in electron counting after learning this concept in lectures typically involves voluminous practice. To enable students to practice electron counting in an interactive and fun fashion, we have adopted game-based learning. In the review by Plass et al. (2015), four key arguments were made for games as an effective learning environment, namely: motivation, player engagement, adaptivity and graceful failure. Inspired by a card game (Thammavongsy, 2020) in the literature, we have developed an educational card game termed "CountQuest" (Tan et al., 2022, Foo & Ang et al. 2023) for revising electron counting concepts taught during CM2111 lectures.

CountQuest utilizes separate metal and ligand card decks (Figure 1). The game is played in groups of 3-5 students and seven ligands cards from the ligand card deck are distributed to each player. Game play starts by revealing a metal card in the metal card deck, followed by players taking turns to place their ligand cards till a certain electron count (typically 18) is reached for the metal complex. Since education games allow for scaffolding of learning (Melero et al., 2011), the players will initially start off with labelled and then proceed to unlabelled ligand cards to increase the difficulty of the game since students will need to use their chemical knowledge to obtain the electron counts of ligands. Ligands were classified based on the Covalent Bond Classification (CBC) or LXZ method developed by Green (1995).

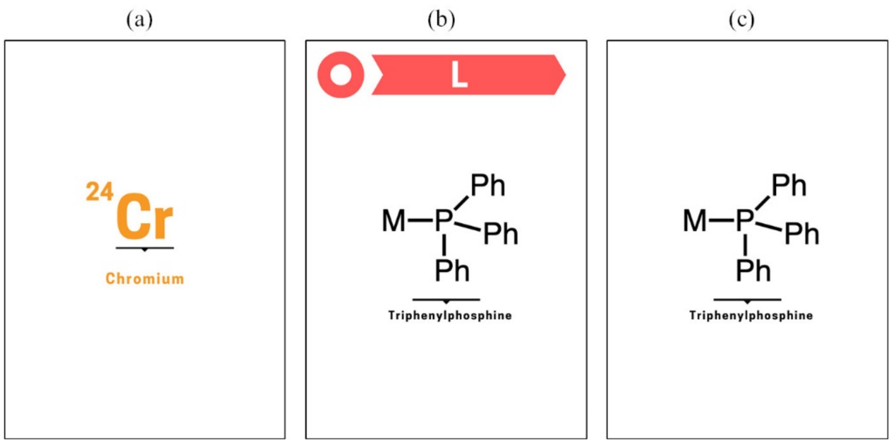

Figure 1: (a) Metal card (b) labelled Ligand card (c) unlabelled Ligand card

In 2019, the first version of CountQuest was mounted using physical cards and the game was played face-to-face in groups of three to five players. In 2020, due to Covid -19 restrictions, all tutorial classes were held online. The game was played online using Zoom with the group facilitator starting the game by screen-sharing a Powerpoint slide with a metal card, followed by the players sketching ligands using the Zoom annotate feature. We have written about this digital version of CountQuest in our previous publication (Tan et al., 2022). This version of CountQuest had some drawbacks as the card deck for each player was pre-assigned and facilitator had to track each card played by the players, which was cognitively demanding for the facilitator.

In 2021, as Covid-19 restrictions continued, an alternative approach was used to mount CountQuest online using a web-based virtual tabletop found on www.playingcards.io for better game mechanics and experience. A virtual tabletop is a digital platform that enables players to meet online and play existing or customized tabletop games (such as board, card, role-playing games) with a playing experience resembling a physical game. Playingcards.io is web-based, free to use and many common card and board games can be found there. More importantly, it allows users to build customized game rooms and import customized card decks and boardgames via a user-friendly interface. This makes it a useful online platform for designing and hosting tailored educational games such as CountQuest. The use of playingcards.io for hosting educational card games during the Covid-19 pandemic is not new (Wilson, 2020). It is important to note that since there is no communication platform in this virtual tabletop, players will have to use existing digital platforms such as Zoom, Skype, WhatsApp, etc to communicate with each other.

Our current work attempts to investigate the following research questions (RQs):

- RQ1: What are students' perceptions of content mastery of electron counting after playing CountQuest?
- RQ2: Do students perform better in an electron counting quiz after playing CountQuest?
- RQ3: How do students perceive CountQuest as a method of learning?
- RQ4: How do students perceive playing CountQuest on a virtual tabletop?

Research Methodology

The study was carried out in a one-hour tutorial session of CM2111 (mandatory year 2 undergraduate inorganic chemistry course) during fall semester of 2021. Students learnt electron counting during a 1.5-hour lecture session and completed a tutorial on the topic about a month before the game session. 79 students participated in this study. Participants completed a pre-game survey and quiz before the game session and a post-game survey (with additional questions) and quiz at the end of the game session. Surveys and Quizzes were conducted in NUS's proprietary Learning Management System, LumiNUS.

Implementation of CountQuest in playingcards.io

The "Custom Room" feature of playingcards.io was used to create the customized game room for CountQuest (Figure 2). The game rules, simplified periodic table for transition metals, Turn and Metal card counter (Figure 2) were added to the gameplay area using the "Edit Table" function. Metal and Ligand cards were imported to their respective decks using the "Custom Card Deck" and "Custom Holder" features. Similar to a physical game, players use the mouse button to play Ligand cards from their hand to the gameplay area, draw and flip Metal and Ligand cards during gameplay. A game round begins by flipping a Metal card, players then play Ligand cards to increase the electron count of the complex to reach its required value. If a player runs out of Ligand cards in their hand to play or cannot play a Ligand card without exceeding the required electron count, they must draw a Ligand card from the deck. The player who played the Ligand card that fulfills the required electron count of the complex and correctly says the oxidation state and *d*-electron count wins the round. To keep track of the number of rounds each player won, the facilitator will increase the respective player's Metal card counter for each round they win.

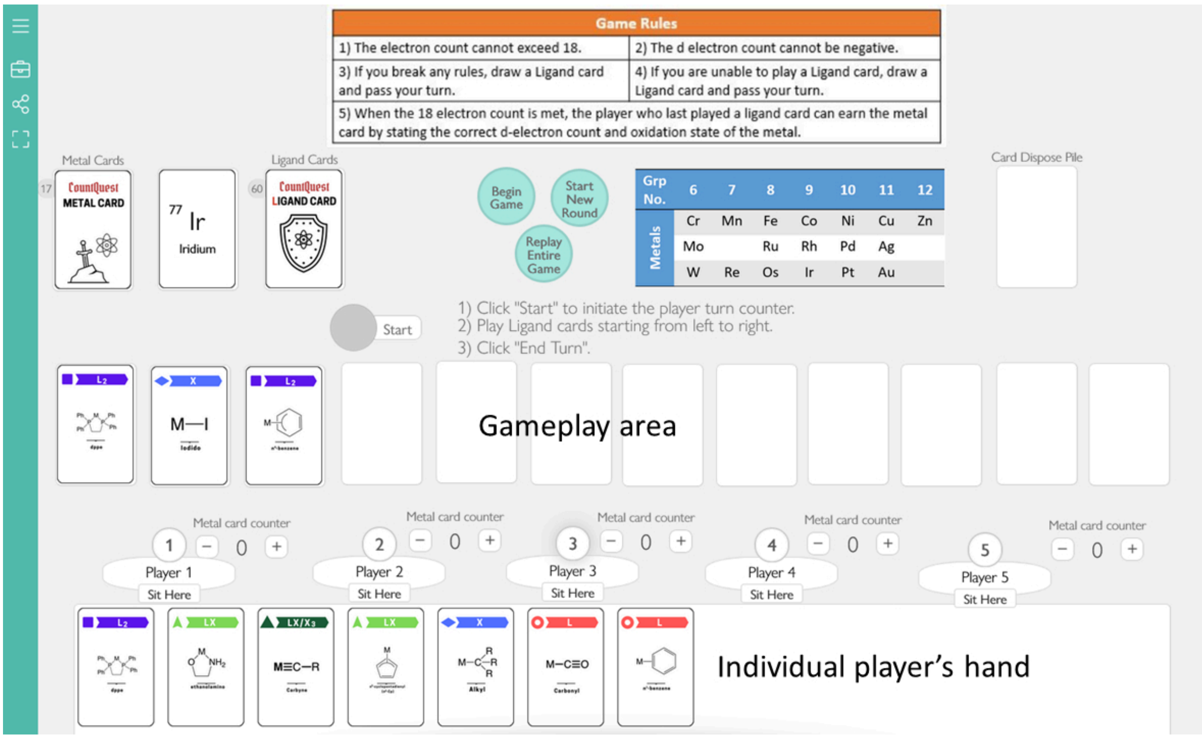

Figure 2: Customized playing table for CountQuest.
Note that the cards in the individual player's hand cannot be seen by other players.

Three levels of CountQuest were developed to scaffold students' learning on electron counting (Table 1). Customized Metal and Ligand cards decks were designed for each level.

Level	Purpose	Required electron count of complex	Ligand Cards
pre-level 1	Familiarize with game rules and refresh lecture on electron counting	18	Labelled
1	Appreciate not all metal complexes have 18 electrons and increase fun factor of the game	variable: 16-21	Labelled
2	Practice electron counting of ligands	18	Unlabelled

Table 1: The three levels of CountQuest played, along with the corresponding purpose, required electron count and the type of ligand cards used for each level.

Results and Discussion

To illuminate the research questions, a survey was administered to obtain student perceptions in the following areas:

(i) content mastery of electron counting
(ii) game design of CountQuest

(iii) CountQuest as a learning method
(iv) playability of CountQuest in a virtual tabletop setting

The results are shown in Tables 2 to 5.

No.	Question	(A+ SA)*%	(A+ SA)*%
		pre	post
1	I had difficulties learning the concept of electron counting.	27.5	17.5
2	I can classify ligands according to the L and X convention.	60.0	77.5
3	I can state the oxidation state and *d*-configuration of the metal in the metal complex.	75.0	90.0
4	Overall, I am confident in electron counting for metal complexes.	32.5	72.5

Table 2: Pre-, post- game survey questions for content mastery (N=40). (A+ SA)% represents the percentage of respondents who rated agree (A) and strongly agree (SA).

From the pre- and post-game survey in Table 2, confidence in electron counting for metal complexes (Q4) has improved as the percentage of respondents agreeing and strongly agreeing more than doubled from 32.5% pre-game to 72.5% post-game (RQ1). This large increase in students' perception of their confidence in electron counting is very encouraging. In addition, the percentage of respondents agreeing and strongly agreeing to specific skills in electron counting such as classification of ligands, oxidation state and *d*-configuration of the metal also exhibited a marked increase post-game.

To determine whether playing CountQuest makes a difference in the quiz scores of students (RQ2), students took a pre- and post-game quiz. The pre- and post- game quiz consist of 5 questions with a total score of 15. The students were shown a different metal complex for each question and asked to write down its three key numerical attributes (electron count, oxidation state and *d*-electron count).

A paired sample *t*-test at 5% significance level was performed to evaluate whether there was a statistical difference between the score of the students in the pre-game quiz and the post-game quiz after playing CountQuest. The results indicated that the post-game quiz scores (M = 12.32, SD = 2.22) were significantly higher than the pre-game quiz scores (M = 14.12, SD = 1.41), $t(56) = 5.753$, $p = < .001$.

No.	Question	(A+ SA)*%
1	The instructions of the game were clearly defined.	87.5
2	The card game was easy to play with prior knowledge of the 18-electron rule.	89.6
3	The duration of the game was just nice	83.3
4	The number of players for the game is just nice	83.3
5	I enjoy playing the different levels of the game	89.6
6	The number of game levels is appropriate	91.7
7	The progression of the game level difficulty is suitable	93.7
8	I enjoy playing the game with the metal card conditions	91.7
9	The card game was fun.	93.7

Table 3: Survey questions for game design of CountQuest (N=48). (A+ SA)% represents the percentage of respondents agreeing and strongly agreeing.

For Table 3, regarding the game design of CountQuest, 89.6% respondents agreed and strongly agreed that the game was easy to play with prior knowledge of the 18-electron rule. In addition, respondents responded favorably to the number and different game levels of CountQuest. More importantly, 93.7% of respondents perceive CountQuest as fun (Q9). Fun has been identified to be pedagogically beneficial (Bisson & Luckner, 1996) as it enhances intrinsic motivation to learn and creates a safe learning environment.

No.	Question	(A+SA)*%
1	I prefer this method of learning compared to the conventional method.	60.4
2	This method of learning is more effective than the conventional method	60.4
3	This method of online learning is engaging.	85.4
4	Playing this game with my peers helps me to identify my misconceptions	83.3
5	I would recommend doing this card game session again for next year's CM2111 class	87.5
6	The different levels of the game reinforce my understanding of the relevant chemistry concepts	91.7

Table 4: CountQuest as learning method (N=48). (A+ SA)% represents the percentage of respondents agreeing and strongly agreeing.

On RQ3 about CountQuest as a learning method, only a slight majority (60.4%) preferred learning electron counting via CountQuest compared to the conventional method (i.e. lectures), with the same percentage saying that it is more effective (see Table 4, Q1 and 2). Interestingly, a large majority (85.4%) agreed and strongly agreed that "this method of online learning is engaging". This suggests that while students think CountQuest played on a virtual desktop is engaging, they are divided on whether it is an effective method for learning the concept compared to conventional method.

No.	Question	(A+SA)*%
1	It is easy to play the game on playingcards.io.	83.3
2	The layout of the virtual play area is clear.	81.2
3	I can play the game without a game master.	58.3
4	I prefer playing the game virtually than face-to-face with physical cards.	33.3

Table 5: Playability of CountQuest on virtual tabletop (N=48). (A+ SA)% represents the percentage of respondents agreeing and strongly agreeing.

For Table 5, regarding the playability of CountQuest on the playingcards.io virtual desktop (RQ4), more than 80% of the students agreed and strongly agreed that it was easy to play the game and the layout of the virtual play area is clear. This suggests that playingcards.io can be used for hosting educational card games and received favorably by students. However only one-third (33.3%) of the students preferred to play the online version of CountQuest than the face-to-face card game version. This is most probably due to the lack of social interactions between players playing an online game compared to a version which is face-to-face. As playingcards.io has limiting scripting ability, CountQuest was played with a game master (facilitator) for each group since the players need to be instructed on the rules and gameplay at the start. When asked whether CountQuest can be played without a game master, only a slight majority, 58.3% of respondents agreed. This indicates the presence of a game master is necessary for optimum gameplay for this version of CountQuest.

As CountQuest was played in CM2111 over three years with different modes of delivery, we compared the students' responses on selected questions regarding confidence in electron counting, peer help for identifying misconceptions and fun element of the game (Qn. A-C) in Table 6:

	2019	**2020**	**2021**
Mode of game delivery	physical face-to-face	online via Zoom annotate	online via playingcards.io (current work)
Qn. A (pre-game): Overall, I am confident in electron counting for metal complexes.	44.1	46.0	32.5
Qn. A (post-game): Overall, I am confident in electron counting for metal complexes.	86.1	81.0	72.5
Qn. B (post-game): Playing this game with my peers helps me to identify my misconceptions.	94.4	84.1	83.3
Qn. C(post-game): The card game was fun.	NA*	79.4	93.7

Table 6: Selected questions for CountQuest played with different modes of delivery for fall 2019 (N=72 for pre and post-game), 2020 (N=63 for pre and post-game), 2021 (N=40 for pre-game, N=48 post-game). Numbers represent the percentage of respondents agreeing and strongly agreeing. *Qn. C was not asked during 2019.

From Table 6, a marked increase in the students' perception of confidence for electron counting from pre- to post-game was seen in all three years showing that CountQuest was effective regardless of the mode of game delivery: physical or online. For Qn.B, a higher proportion of students perceived the physical version in 2019 to be more effective for peer help compared to the online versions played in 2020 and 2021. This suggests that peer learning is more effective in a physical face-to-face than in an online environment due to increased social interaction. This finding is consistent with previous work in the literature which indicated that face-to-face mode of game-based learning is perceived more favorably than online on aspects such as overall effectiveness and fun element (López-Fernández et al., 2023). In addition, Qn.C indicated that students perceived the current online version of CountQuest mounted on playingcards.io (93.7%) as more fun than the online version via using Zoom annotate in 2020 (79.4%). This is most probably due to the smoother game mechanics/interface using a virtual tabletop compared to annotating on a shared screen in Zoom.

Conclusion

A web-based virtual tabletop, playingcards.io was used to mount an online version of an electron-counting card game, CountQuest developed at the National University of Singapore. Students from the module CM2111: Inorganic Chemistry 2 played this game for an hour in the fall of 2021 after lectures on electron counting. Pre- and post-game surveys demonstrated increased confidence in electron counting which is further corroborated with a statistically significant gain in post-game quiz scores. Comparison of different modes of delivery (physical, online) for CountQuest all indicate an increase in CM2111 students' confidence in electron counting after playing the game. These results are encouraging and demonstrate that appropriately designed tabletop games played physically or online can be used to revise classroom concepts with an increase in student confidence and learning.

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